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DESIGN & FABRICATION OF AN AIRBORNE
REMOTE SENSING SYSTEM FOR GAS PIPE-
LINE LEAK DETECTION

DSS File No. 15SQ.23440-0-9103



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PHASE II - Design, Construction &
Laboratory Testing

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72pp

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1.0 PROJECT DESCRIPTION

1.1 Summary

MONITEQ has constructed a remote sensing instrument called GASPILS (Gas Pipeline Leak Detection) to detect gas leaks from underground pipelines, and laboratory tests indicate that the sensitivity performance required for successful field operation has been achieved.

1.2 Introduction

This document describes GASPILS, a gas pipeline leak sensor. GASPILS is a self-contained passive electro-optical instrument for airborne use which detects in real time the gas emanating from an underground pipeline leak. It therefore provides a direct and immediate indication of the presence of a leak when operated on routine pipeline patrol flights.

This document is the final project report, "Design and Fabrication of an Airborne Remote Sensing System for Gas Pipeline Leak Detection" conducted under DSS Contract #15SQ.23550-0-9103, serial #1SQ81-00003, with contributions from CANMET of the Department of Energy, Mines and Resources and Transport Canada. It covers in particular the details of the instrument design and performance evaluation, and supplements the detailed description of the detection principle and theoretical performance contained in the Conceptual Design Report, MTR#81-27, August 1981.

Given the successful laboratory results presented herein, GASPILS is ready for field evaluation flight trials to determine its performance under varied actual conditions. These measurements will lead the way to placing GASPILS into operational service to enable leaks to be detected before they can develop into dangerous and costly incidents.



1.3 Detection Principle

Gas leaking from an underground pipeline diffuses through the overlying fill, reaches the surface and mixes with the atmosphere above the ground, causing an anomalous local concentration of the pipeline gas. Natural gas is the normal material transported by gas pipelines (as opposed to coal gas) and consists principally of methane, CH_4 , with other minor constituents such as ethane, C_2H_6 . Because these substances have well defined infrared spectra which are distinct from the normal atmospheric constituents (nitrogen, oxygen, water, etc.), their presence can be determined by monitoring the blackbody radiation emitted by the ground and atmosphere from a downward looking airborne sensor and detecting the infrared spectral absorption or emission caused by the leak gas.

In order to detect the small leak, the instrument must have a high sensitivity (a few parts per million metre: ppm.m). To achieve this, the instrument must have a large light gathering capability and be specific to the gas to be detected. GASPIILS achieves these requirements using the non-dispersive gas filter correlation (GFC) technique, in which a sample of the gas to be detected acts as an optical filter for the radiation collected by the sensor. The technique has high throughput because of its large etendu (aperture solid angle product) and because of its wide spectral bandwidth. In addition it has high specificity because the gas sample is a matched filter to radiation affected by the target gas. By definition, being specific to the target gas necessarily means that the instrument is not sensitive to other gases mixed with it in the atmosphere. Both these features give the technique a strong advantage over competing techniques, in addition, the sensor is kept optically simple, which has obvious benefits.

The GFC measurement technique as implemented in GASPIILS compares the radiance signals reaching a single detector from three sectors seen sequentially:

- 1) a reference black body (called the "blank")
- 2) the ground and intervening atmosphere seen through a cell containing the target gas
- 3) the same ground and atmosphere seen through a cell (called the "reference"), which does not preferentially absorb at the target gas absorption lines.

The two cells and the black body are maintained at the same temperature so that only changes in the radiation entering the instrument affect the sensor's signal. Figure 1.1 shows the basic elements of the sensor.

The radiation seen through the two cells are the key to the technique. The correlation gas cell constitutes an optically thick medium at the centre of the characteristic wavelengths of the target gas, so the presence of the target gas in the atmosphere, which absorbs the radiation at the same wavelengths, has no significant effect on the radiance signal through the correlation cell. On the other hand, the information on the absorption is transmitted through the reference cell because the reference cell does not absorb at the wavelength. This principle is illustrated in Figure 1.2.

There are certain difficulties with this type of measurement which were discussed in detail in the Conceptual Design Report. These are due to such factors as the competing thermal radiation from the target gas, the ambient concentration of the target gas in the atmosphere and the spatial variation of the ground emissivity. Two methods have been suggested to overcome these complications. The first, which has been implemented in Phase II, is to detect two gases present in the leak, namely methane and ethane, and to measure the ratio of their concentrations.

GASPILS

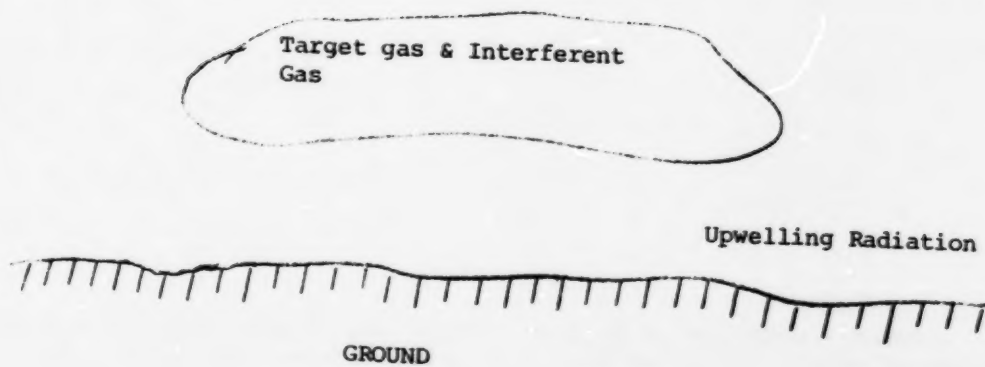
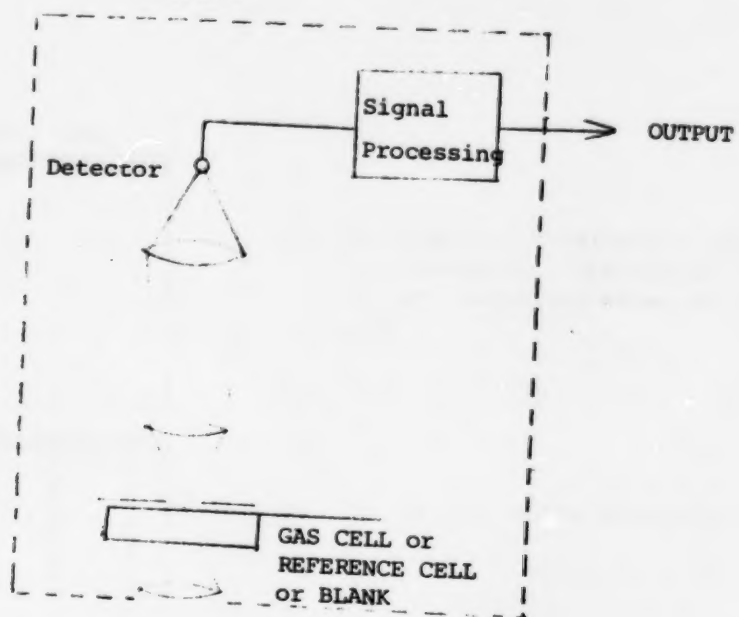
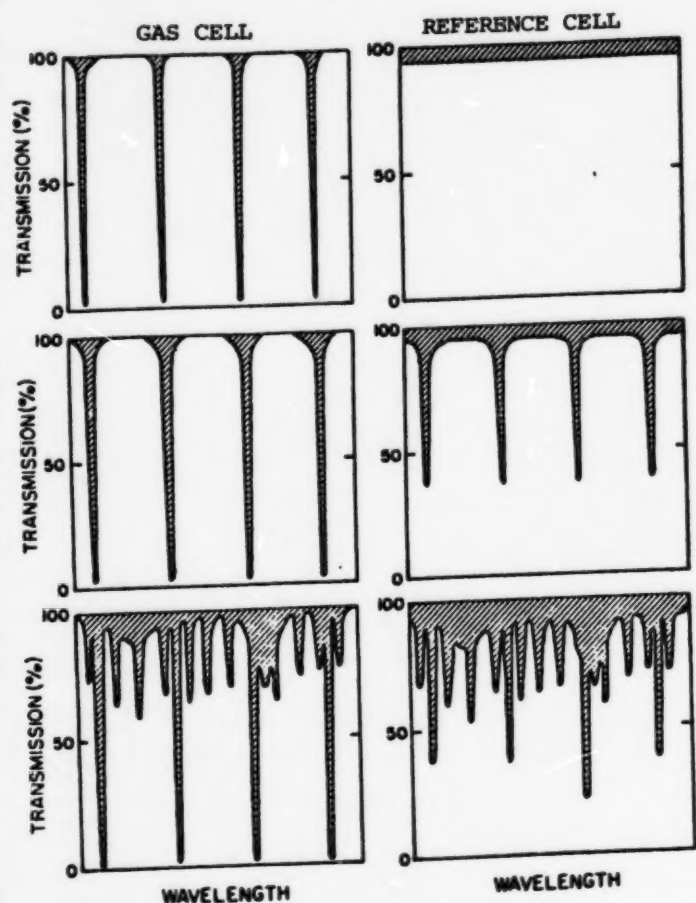


Figure 1.1: Basic elements of GASPILS



(a) No target or interferent gas in atmosphere. Absorption lines of the target gas shown at the left

(b) Target gas in the atmosphere

(c) Target and interferent gases in the atmosphere

Figure 1.2: Principle of gas filter correlation detection. Spectra of the radiation from a uniform background source reaching the detector after passing through gases in the atmosphere (top to bottom) and through the target gas cell (left) or reference cell (right). The detector signal is proportional to the area under the curves (white).

is to convert the ethane cell to nitrous oxide, N_2O , and to ratio the CH_4/N_2O measurements. This method has the advantage of using a gas, N_2O , which is presumed to be mixed, in the atmosphere, in a similar manner to CH_4 . Thus changes in CH_4 response due to the background CH_4 effects should be compensated by similar changes in N_2O and the ratio CH_4/N_2O should be indicative to true changes in the concentration (leaks) of CH_4 .

1.4 General Description of GASPILS

The sensor consists of two basic elements as shown in Figure 1.1. One, the optical system, and two, the signal processing electronics system. There are in fact two optical trains, one for methane detection and the other for ethane, and they share a common assembly for introducing the correlation gas cell, the reference cell and the blank into the optical paths. This consists of a rotating disc containing the gas cells. These cells are located in an insulated housing which is maintained at a constant temperature by a pair of thermo-electric devices, $\pm .5^\circ C$ required as indicated in the Phase I Report. This disc is called the chopper wheel as it chops the signal reaching the detectors. Each detector has an integral cryostat which is cooled by a high pressure gas flowing open loop through Joule-Thomson expansion devices. The arrangement of all these devices is illustrated in Figure 1.3.

The two optical trains are identical and straightforward. They gather radiation from an 8° field of view, pass it through the chopper wheel, filter it, and measure it by the detector. Only three single element lenses are used, but these are made of germanium to pass the wavelengths used. The wavelength range seen by the detectors are defined by the filters: for methane, a band of $0.29 \mu m$ wide at $7.91 \mu m$ is used, whereas a band $0.31 \mu m$ wide at $12.16 \mu m$ is used for ethane. Both detectors are photo-conductive mercury-cadium-telluride devices operated at 77K. Figure 1.4 shows the optical train components.

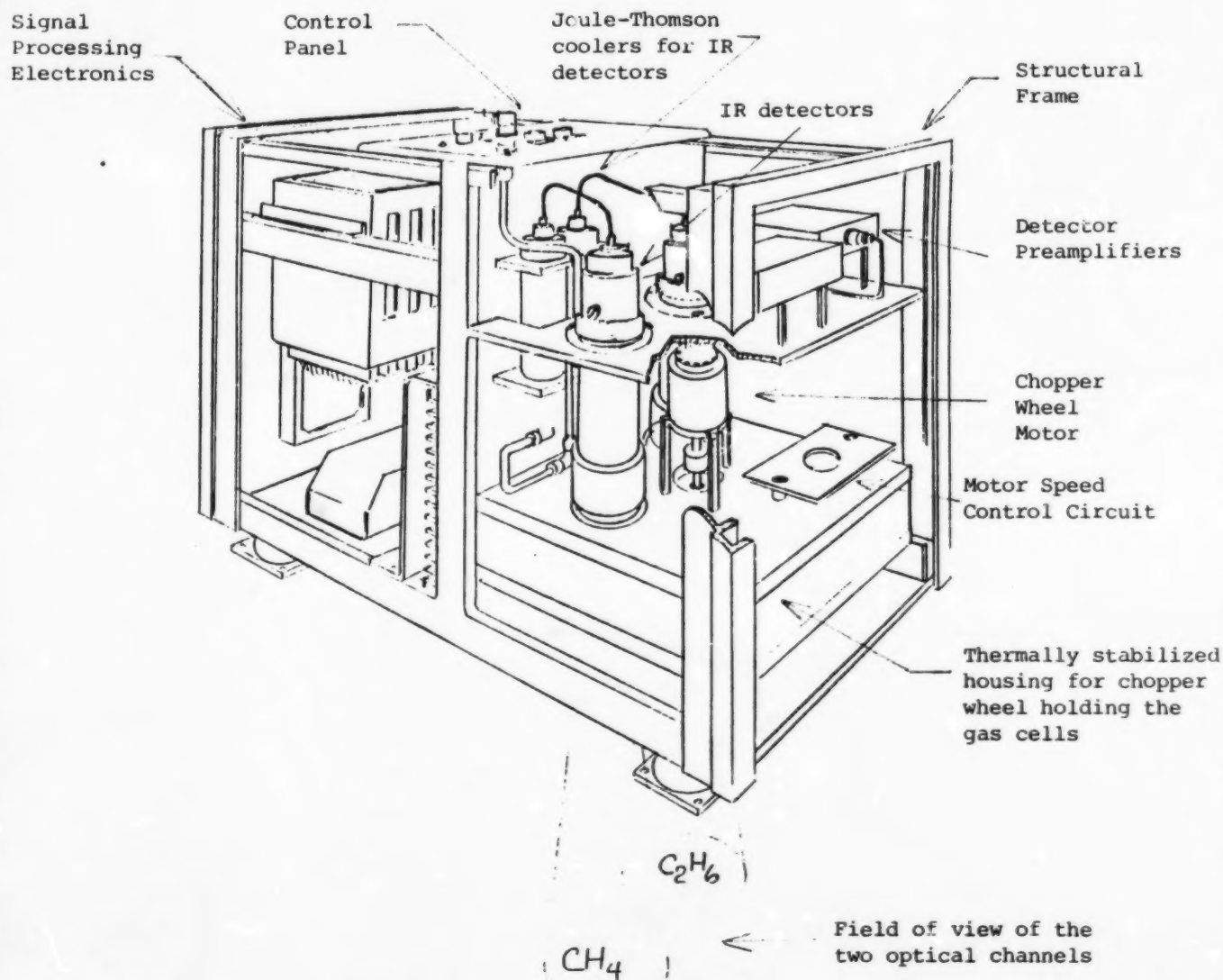


Figure 1.3 : Illustration of the GASPILS sensor with the external cover removed.

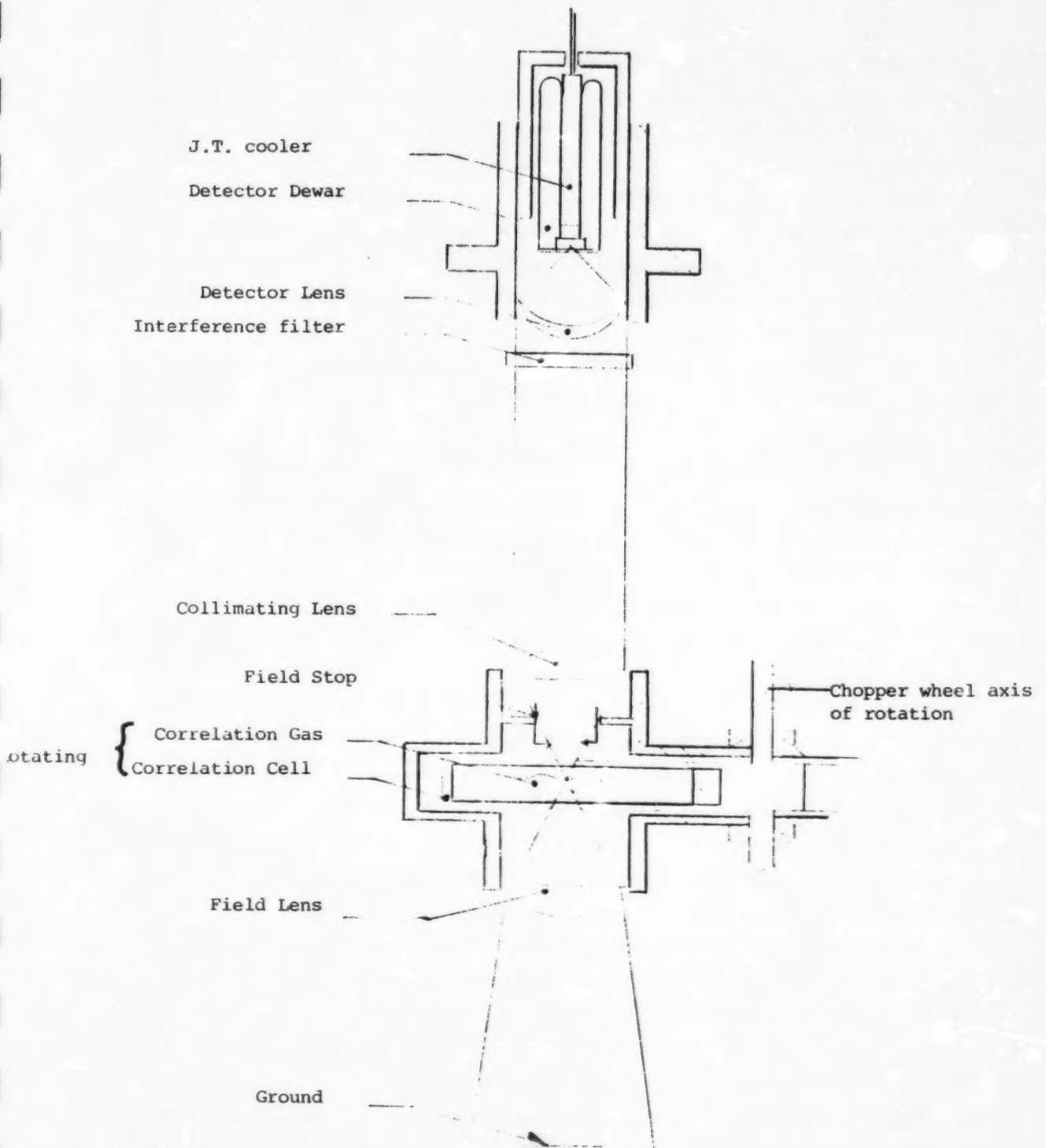


Figure 1.4: Schematic of An Optical Train

Since both optical trains share the chopper wheel, it has to provide correlation gas cell, reference gas cell and blank sector for each train. This is achieved by locating these on two tracks at different distances from the rotation axis and using 120° arcs for each sector. In order to accommodate the diameter of the lenses, the two optical trains do not share a common radius, but are separated by 120° . Two additional tracks at the periphery of the chopper wheel provide sector identification and synchronization information to the signal processing electronics using LED-photodetector pairs. Figure 1.5 shows the arrangement of the components of the chopper wheel: note that a single cell is used for the reference for both the methane and ethane channels.

The chopper wheel is enclosed in a thermally insulated box whose interior temperature is maintained at a preset value by means of a pair of thermoelectric coolers and a control circuit. A constant temperature is needed because it defines the radiance value seen by the detectors during the blank sectors, which itself is used by the signal processing as a standard level. A stability of 0.5K is needed, and is certainly achieved.

As the chopper wheel spins at approximately 1000 rpm, the detectors see each sector for about 20 ms. They provide an electronic signal proportional to the amplitude of the radiation reaching them for the total of six distinct conditions (three sectors and two tracks). These are amplified in two stages, filtered and digitized with 16 bit resolution. The remaining processing consisting of arithmetic operations on the six signals, is performed by a Z-80 microprocessor which yields five numerical outputs in digital form at an external connector (RS-232 output port). These are also provided in analog form on another connector. In addition, there are two alarm outputs, one visual (an LED) and the other aural (a tone), which are set to activate at a threshold value of detected gas leak.

The sensor's controls as well as input and output connections are all located on a panel at the top of the instrument. Because the functions of the instrument are so autonomous, very little manual intervention is required. Inputs consist of 28 VDC power and a flow of high pressure dry



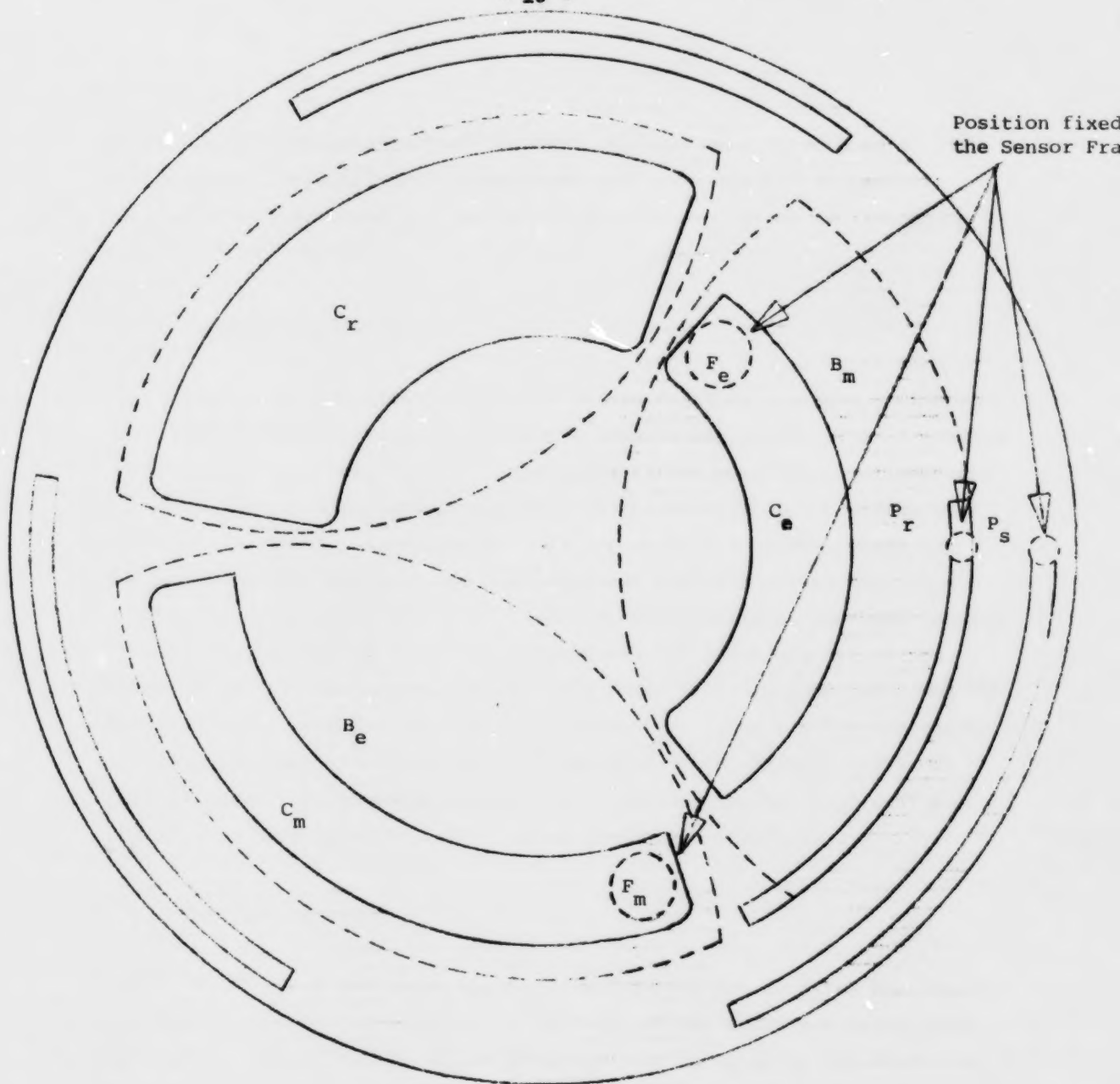


Figure 1.5: Bottom View of the Chopper Wheel

- C_r, C_m, C_e - Windows for the correlation cells of reference, methane and ethane gas respectively. The actual gas cell location is indicated by the dotted line.
- F_m, F_e - Field stops for methane and ethane channel respectively
- B_m, B_e - Blank sectors for the methane and ethane channels respectively
- P_r, P_s - Pick-offs for the reset and sector synchronization signal respectively.

nitrogen (for the Joule-Thomson coolers), whereas outputs consist of the five signals in digital and analog form, the audio and LED alarms, and a LED status indication of D/A conversion overflow. Control is limited to a single on/off switch.

1.5 GASPILS Performance

The evaluation of GASPILS' performance has so far been confined to laboratory experiments, but the results show a sensitivity of 70 ppm.m of methane and 750 ppm.m of ethane for 4°C temperature difference. Simple laboratory procedures indicate the sensor performs satisfactorily in the presence of vibration and E.M.I. Stability is good for as long as a day, which is adequate for field trials. The stability has not been tested for longer periods. Certain areas where the sensor's design could be improved leading to enhanced sensitivity have been identified, but these are not serious enough to require implementation before a field trial is undertaken and the situation is normal for any prototype device. Because the present performance is encouraging for pipeline leak detection requirements, the known areas of suggested improvements plus those derived from a field evaluation program will lead to a promising future for GASPILS technology.

1.6 GASPILS Operation

Because GASPILS has only been operated in a laboratory to date, the field operation procedures proposed so far have not been tested and modified by experience. The objective of the procedures is to optimize the detection performance depending upon controllable and environmental factors such as ground surface temperature, surface morphology, wind velocity, solar radiance, aircraft flight path (relative to the pipeline), ground speed and altitude, and pipeline gas composition. As occurs during the deployment into service of any item of technology, the operational procedures are as important to the successful performance of the item as the technology of the item itself, and improvements in performance over initial values are normally obtained as operational experience is gained. Consequently, it is



natural that these procedures will not have been developed during the prototype hardware development stage which is the subject of the report, but it is equally important to devote the attention needed to optimize them in order to fully utilize the capabilities of the hardware.

At this time, GASPILS is proposed to be operated from an aircraft (or helicopter) viewing straight downward at the ground without intervening windows while flying at up to 120 knots, 500 to 1000 feet above the ground. The flight track should be over or downwind from the pipeline to encounter the dispersed gas plume. Strong or gusty winds will disperse a plume more rapidly, thereby reducing the detection sensitivity so these conditions should be avoided if possible. It is expected that more detailed procedures will be proposed following the flight tests.

1.7 GASPILS Summary

The following summarizes the specifications of GASPILS:

Description:	A passive electro-optical sensor for airborne use for real time detection of gases emanating from a pipeline leak with a source temperature of 30°C and a gas temperature of 26°C.
Detection Limit:	(a) Noise equivalent signal 70 ppm.m for methane (b) Noise equivalent signal 750 ppm.m for ethane (to be improved).
Dimensions:	56 cm high by 46 cm long by 28 cm wide.
Field of View:	8 degrees (70 m footprint at 500 m flight altitude).
Mass:	25 Kg

Construction: Shock protected for airborne operation by four
TTN-A-3 Barry mounts which is rated for 15 lb/mount.

Input Requirements: (a) power: 28 VDC 11A (300W)
(b) dry nitrogen gas from a 1200 to 3000 lb/in²
pressure source (0.02 m³ of 2500 psi N₂/hr).

Outputs: (a) Visual gas leak alarm
(b) Audio gas leak alarm
(c) Five digital words of gas signals, radiance signals
and the ratio signal ASCII format
(d) Analog signals equivalent to the digital signals.

Recommended
Auxiliary Equipment: (a) Chart recorder (for analog signal)
(b) Data printer or data logger (for digital
signals) coupled to a time code generator and
navigational data.

1.8 Scope of Report

The remainder of this report provides a detailed description of the GASPILS design and initial performance data to elaborate the description provided thus far. Also referenced are electrical schematics, assembly drawings and vendor data to ensure a full and accurate evaluation of the sensor and its development. The detailed full scale drawings, and parts list are supplied separately in Appendix III.

2.0 OPTICAL AND MECHANICAL DESCRIPTION

2.1 Introduction

The GASPILS sensor optics is designed to fulfill the requirements of high sensitivity and high specificity. The optical speed and field of view are optimized to obtain high spatial resolution and stability. The light gathering optics are designed to focus incoming light onto the small area detector, and yet provides fine adjustment and maintains a high degree of stability. The sensor is ruggedized to withstand the environmental conditions of the aircraft platform. These include the temperature range, mechanical vibration and electromagnetic interference. Care has been taken to minimize the size and weight of the sensor.

2.2 Optics

Each optical channel of GASPILS operates in the infrared spectrum; one channel for methane at 7.91 μm and the other channel for ethane at 12.16 μm . These spectral bands have been selected in bandwidth and location to optimize the sensor performance in the field operation.

Germanium lenses and Irtran II windows are used. The high transmittance of both Ge and Irtran II together with their anti-reflection coatings and flat spectral characteristics (less than 1% change) between 7 and 12 μm make the channel optics similar and cost-effective. Optimization of the lens focussing is achieved by adjustable lens mounts. The spectral filters are custom designed to have locations and widths which optimize performance. Simple in-line symmetry and rugged optical design practice is employed throughout.

2.2.1 Optical Configuration

A dual channel configuration sharing one chopper wheel was chosen to obtain high sensitivity and stability, as discussed in the previous conceptual design report. Two optical trains collect incoming light from two different cells simultaneously at different radii of the chopper wheel, as shown in the schematic diagram of the chopper wheel assembly (Figure 1.5). The optical trains are mounted vertically each having a field lens near the bottom of the chopper wheel housing and collimating lens near the top side of the chopper wheel housing. The lenses thus seal the chopper wheel housing. The interference filter, detector lens and the detector for each channel are assembled as independent units, which are mounted on a structural shelf and rigidly connected to the chopper housing via the frame of the instrument. A slide-fit shroud is used to complete the optical train. A schematic of the entire optical assembly is shown in Figure 1.4.

The lens system is designed to provide an 8° field of view and to focus the collected light onto the 2 mm x 2 mm detector area. The detector lens is designed to focus the field lens on to the detector (see Figure 2.1), to reject correlation between the source pattern and any optical elements.

2.2.2 Gas Cell and Chopper Wheel Design

A unique design of the chopper and cell configuration was developed in the GASPILS sensor to obtain maximum duty factor and to simultaneously accommodate two optical channels. The maximization of the duty factor has been accomplished by using only three gas cells one for methane gas, one for ethane gas, and the other for dry-nitrogen gas (the reference cell). The design yields on minimum weight for the chopper wheel. The cells are located in an aluminum wheel in the sequence of ethane, dry-nitrogen and methane cells in counter-

GE. LENS 1

$r_1 = 53 \text{ mm}$

$r_2 = 79.6 \text{ mm}$

$t = 1.96 \text{ mm}$

DIA. 27.4 mm

$f_l = 48.3 \text{ mm}$

GE. LENS 2

Telescope
Lens

Relay
Lens

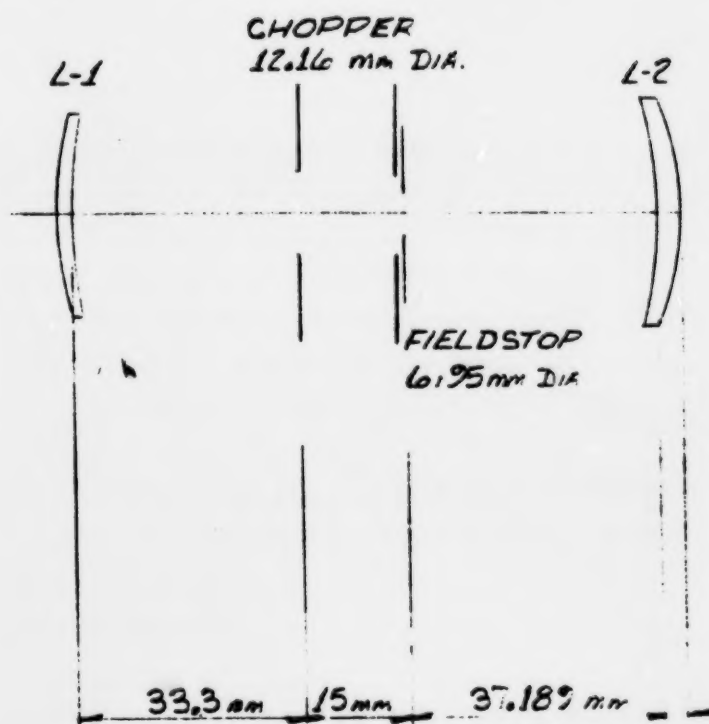


Figure 2.1 : Sch
len

GE. LENS 1
 $r_1 = 53 \text{ mm}$
 $r_2 = 79.6 \text{ mm}$
 $t = 1.96 \text{ mm}$
 $\text{DIA} = 27.4 \text{ mm}$
 $f_L = 48.3 \text{ mm}$

GE. LENS 2
 $r_1 = 44.04 \text{ mm}$
 $r_2 = 65.61 \text{ mm}$
 $t = 3.28 \text{ mm}$
 $\text{DIA} = 34 \text{ mm}$
 $f_L = 37.19 \text{ mm}$

GE. LENS 3
 $r_1 = 22.35 \text{ mm}$
 $r_2 = 92.46 \text{ mm}$
 $t = 6.7 \text{ mm}$
 $\text{DIA} = 40 \text{ mm}$
 $f_L = 12.43 \text{ mm}$

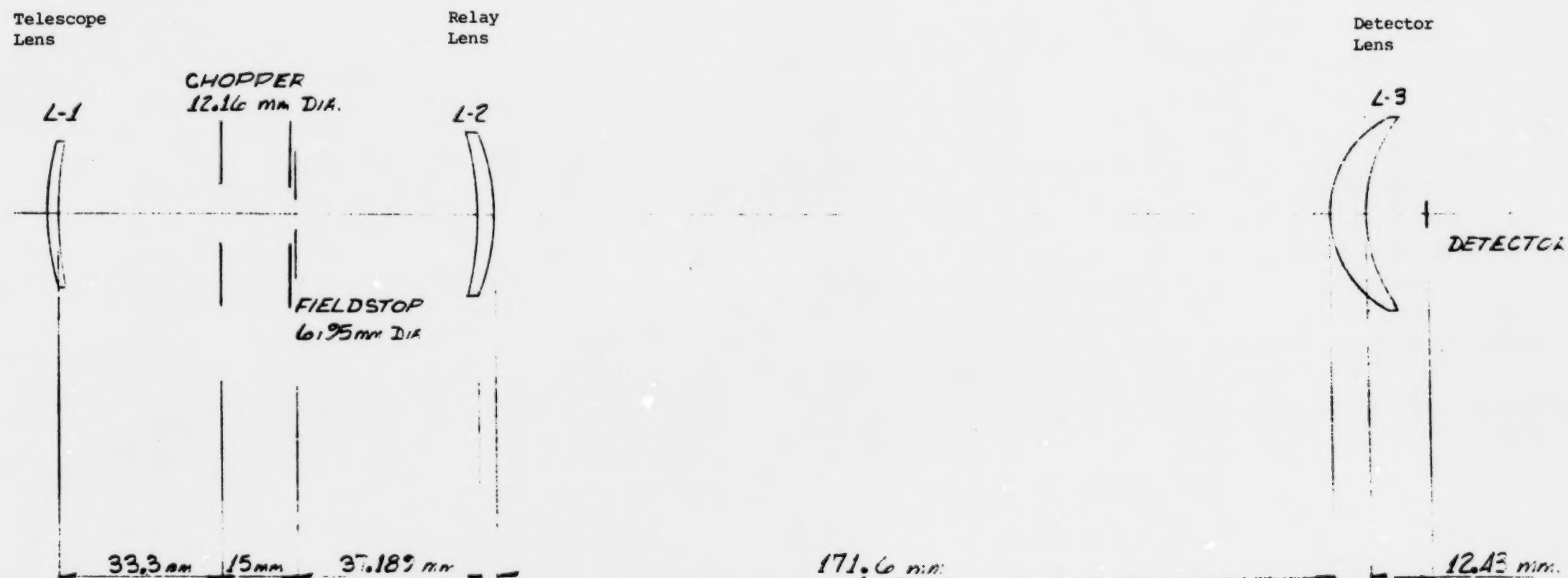


Figure 2.1 : Schematic of the Optical Configuration and the lens parameters of the GASPILS sensor.

clockwise direction when viewed from the detector. The cells are mounted on the chopper wheel between a set of rubber gaskets and the covering flange to withstand the force due to the chopper rotation. An opaque plastic mask with slotted sectors covers the mounted cells to provide windows and blank sectors in sequence for each channel. Rotation of this disc causes the signal output shown in the upper half of Figure 2.2. The mask is coated with a high emissivity (approximately 0.95) Nextel paint to provide a blackbody radiance at the temperature of the correlation gas which is required in the signal processing algorithm. The chopper wheel is required in the signal processing algorithm. The chopper wheel is covered by a 1/16 inch aluminum plate with three quarters matching the cells. In this way the symmetry and mechanical balance of the chopper wheel has been achieved.

A gas cell consists of a cell body made of 1 cm pyrex glass walls and a pair of Irtran windows. The oval shape of the cells is obtained by, fusing two cut out pieces of a circular cylinder. The windows are glued to these walls. The cells were then evacuated and filled with the appropriate gas at one atmosphere pressure. Absorption spectra of the cells were obtained four days after the cells were prepared, and are shown in Figure 2.3. The low transmittance of the cells is due to the uncoated windows.

The synchronous timing mark for the pick offs (HEDS-1000) indicate rotation and sector position, provided from the opposite side of the chopper wheel.

2.2.3 Detector Assembly

The small detector area and the beam spot size requires a special design by which the light gathering efficiency (overlapping of the detector area and the beam spot) and the optical stability are optimized. The high optical stability (especially short term stability) is required lest the sensor should give any false signal associated with the optical alignment.



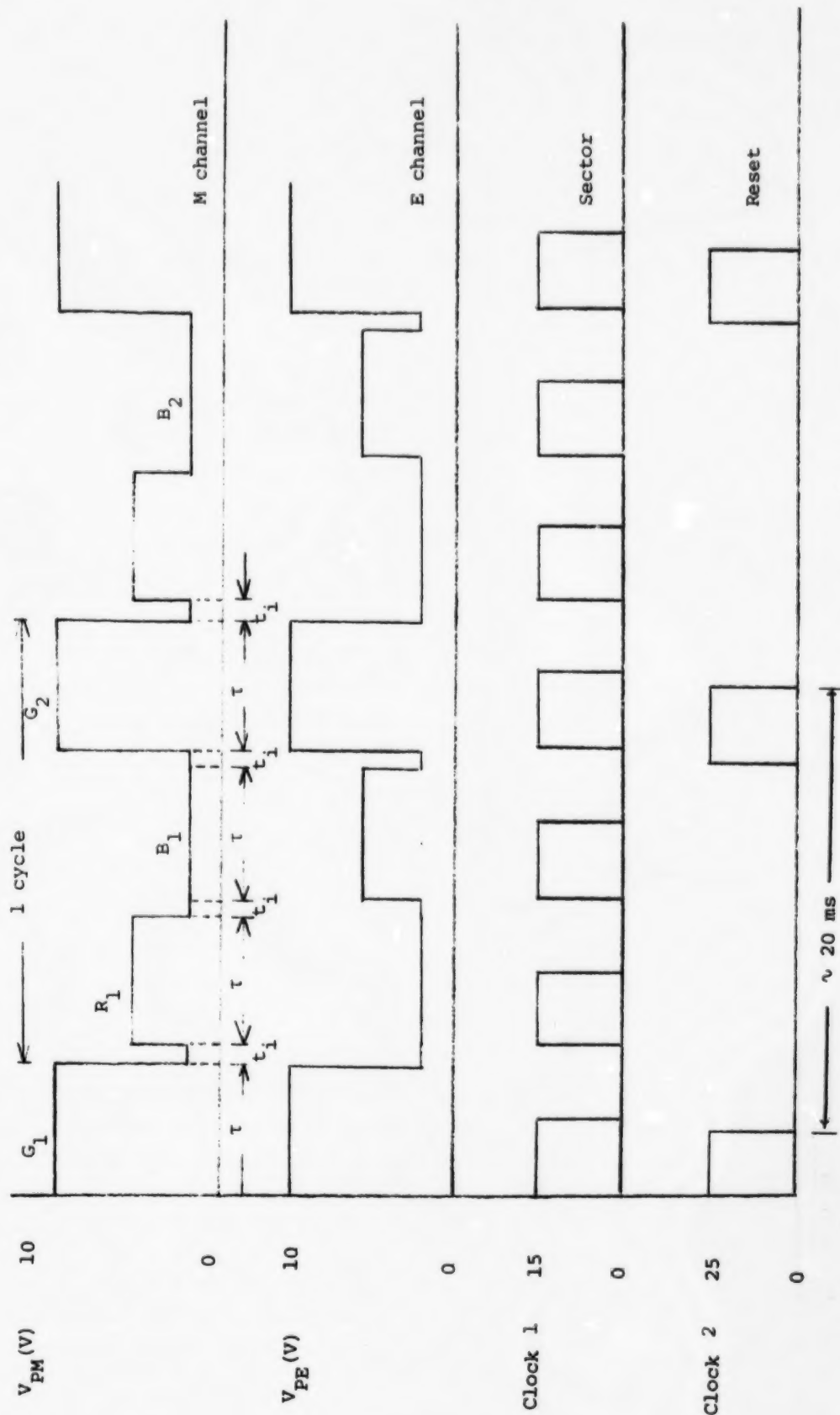
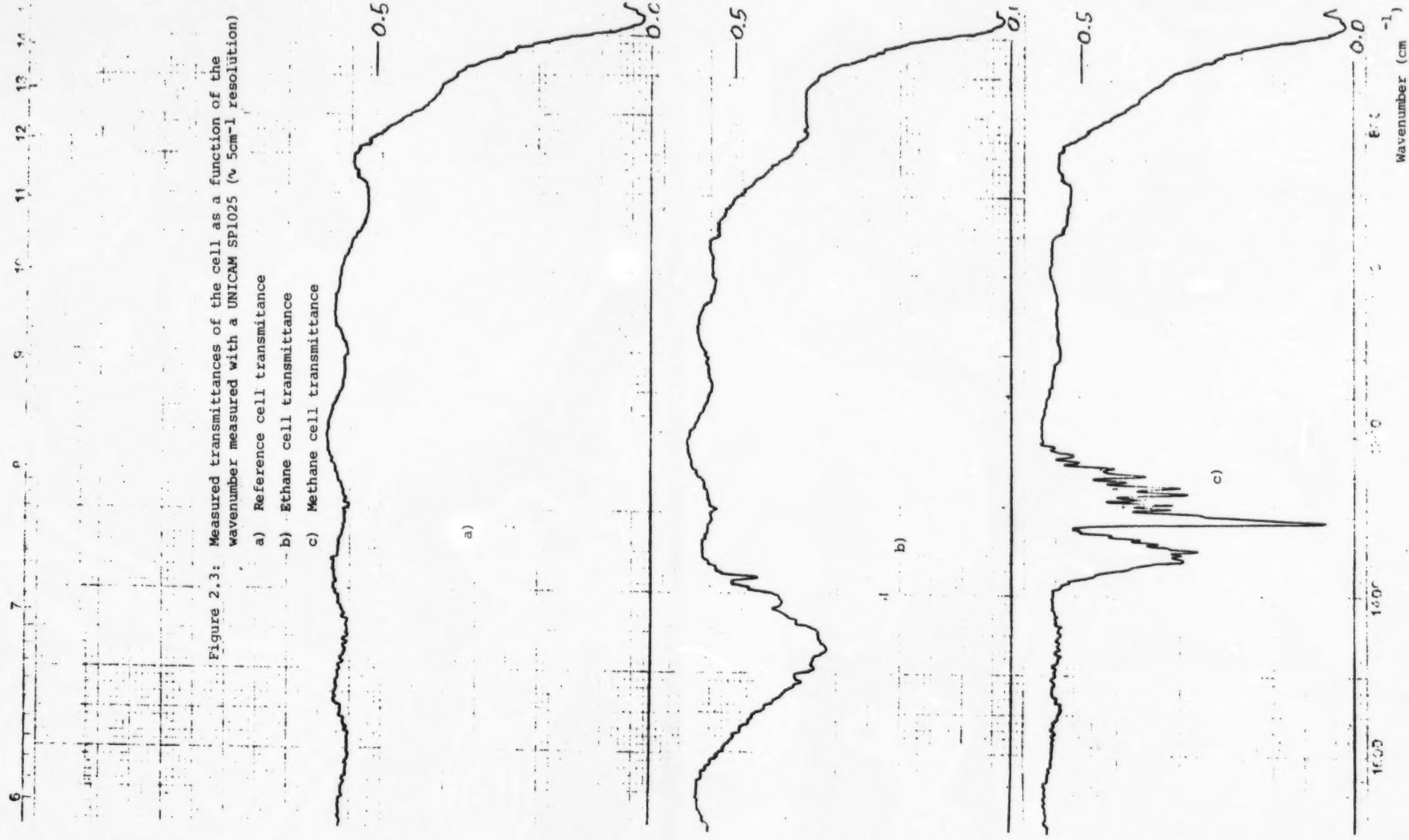


Figure 2.2: Schematics of the radiation signal sequences for M and E channel and clock signals - G: gas cell; R: reference cell; B: blank sector



The detector is mounted coaxially in a cylindrical barrel together with the detector lens and interference filters so that focus can be obtained by adjusting the distance between the detector and lens. Fine adjustment is done by adjusting the horizontal position of the whole detector assembly (see Figure 1.4). Final alignment is achieved by positioning the detector lens assembly.

The detector cooling gas for the Joule-Thomson cryogenic system is fed from the top and the exhaust gas is taken out at the top flange to isolate the optics from the cooling system. The interference filter shields the detector from the external thermal radiation except for a narrow spectral band associated with the target gas spectrum. A cylindrical shroud connects the collimating lens and the detector lens and completes the optical train of the GASPILS sensor.

2.3 Mechanical Description

The GASPILS sensor is designed as an airborne sensor to withstand a wide range of temperature variations, aircraft vibrations and electro-magnetic interference. It also is subjected to the requirement of small volume and weight.

As shown in the illustration of the sensor in Figure 1.3, the sensor is housed in an aluminum frame structure with a middle partition. The frame is welded 1.5" x 1" T-shape angles. A $\frac{1}{4}$ " thick aluminum plate is welded at the bottom to form a baseplate of the sensor. The baseplate, partition and the upper plate form a rigid three-dimensional structure on which the optical components are mounted. The electronics components are situated on the other side of the partition. The chopper with gas cells is enclosed in a rectangular housing constructed using $\frac{1}{4}$ " aluminum plates. A $\frac{1}{4}$ " copper plate

on one face of the box and a pair of thermo-electric coolers and a temperature sensor are mounted on this copper plate. There are four germanium lenses mounted on the top and bottom plate of the box as part of the optical train (see Section 2.2). $\frac{1}{4}$ " Nylon plates cover the box to provide thermal insulation so the temperature of the entire box including the gas cells and chopper wheel can be controlled at a fixed value independent of the ambient temperature. An aluminum heat sink is attached on the opposite side of the TE cooler and a 100 CFM fan is mounted on the heat sink. The assembly of the chopper wheel and the temperature controller box is shown in Figure 2.4.

The motor which drives the chopper wheel is mounted on the top plate of the box and the motor shaft and chopper wheel shaft are connected by a flexible coupling. The motor speed control electronics are mounted on the top of the nylon insulator box to isolate electric noise.

The temperature controller box, including the chopper wheel and motors can be disconnected from the system by undoing the screws which fasten it onto the frame of the sensor. A Cannon connector is provided to disconnect the electronics on the box from the system electronics. The detector assembly situated on the top plate can be disconnected by lifting the shrouds off the collimating lenses.

The control panel is mounted on the top face of the sensor. The power connector and switch, analog and digital output connectors, audio and LED alarm, fuses, and the swage-lockquick connector for the Joule-Thomson cryogenic system are all mounted on this panel.

Four shock absorbers are mounted at the corners of the baseplate to isolate aircraft vibration.

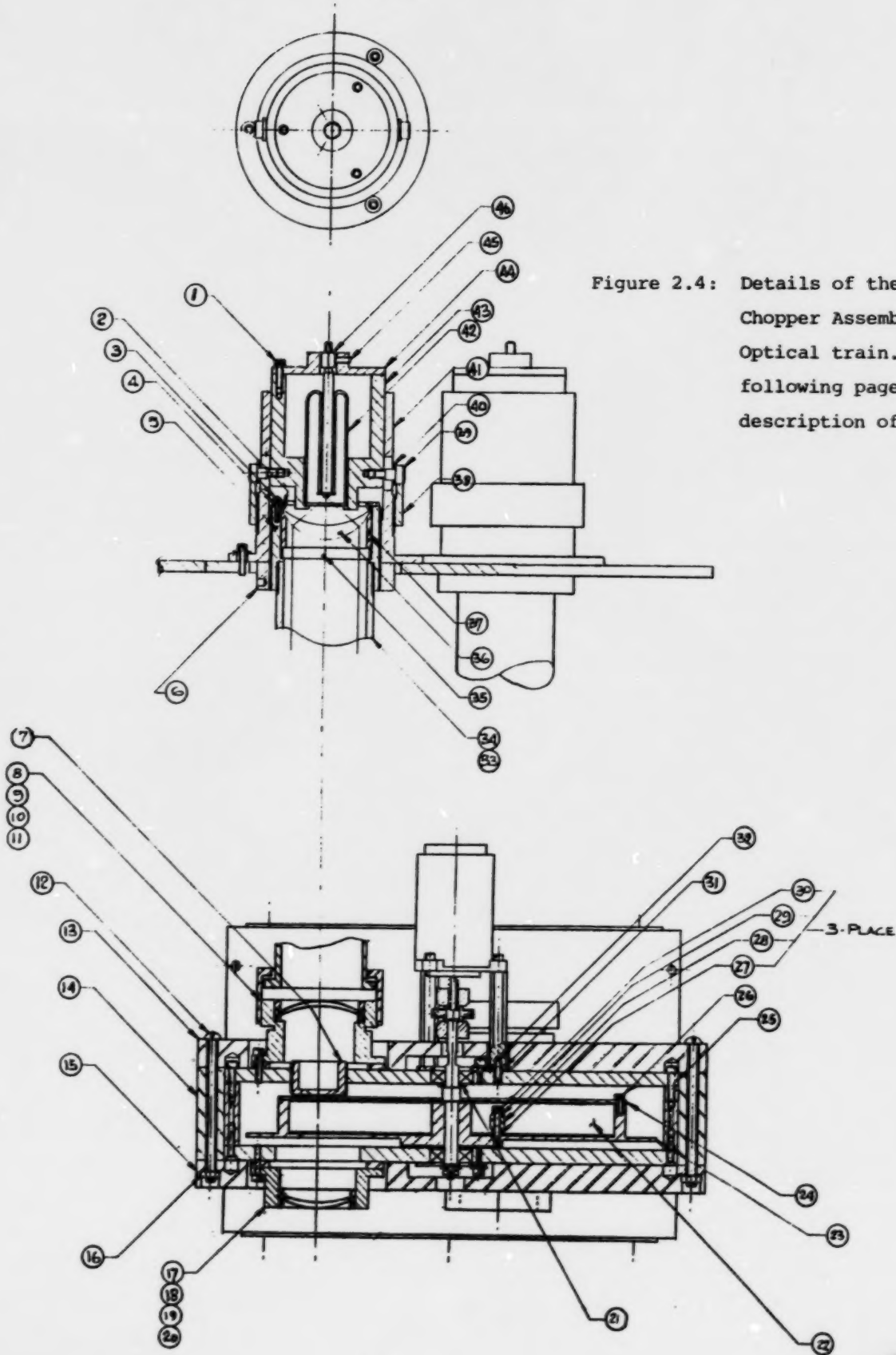


Figure 2.4: Details of the Chopper Assembly and Optical train. See following page for description of parts.

Figure 2.4 : Parts List

- | | | | |
|-----|------------------------------|-----|-----------------------------------|
| 1) | Screw #4-40 UNC | 32) | Screw, #4-40 |
| 2) | 'O' Ring | 33) | Tube |
| 3) | Screw #2-56 | 34) | Ring, Sliding |
| 4) | Plate, lens retaining | 35) | Filter |
| 5) | Housing, Lens & Filter (L3) | 36) | Lens, L3 |
| 6) | Ring, clamping | 37) | Support, Lens |
| 7) | Fieldstop | 38) | Ring, Focus adjustment |
| 8) | L ₂ Lens Assembly | 39) | Screw, Shoulder |
| 9) | Screw, #4-40 | 40) | Washer, Nylon |
| 10) | Insulator, Lens | 41) | Support, Cryogenic & Upper Optics |
| 11) | Lens | 42) | Detector Assembly |
| 12) | Screw #8-32 | 43) | Housing, Detector & Cryostat |
| 13) | Insulator - Upper | 44) | Plate |
| 14) | Insulator - Side | 45) | Set Screw, #4-40 |
| 15) | Insulator - Lower | 46) | Cryostat |
| 16) | Nutsert, #8-32 | | |
| 17) | L ₁ Lens Assembly | | |
| 18) | Screw, #4-40 | | |
| 19) | Insulator, Lens | | |
| 20) | Lens | | |
| 21) | Belleville Spring | | |
| 22) | Cell | | |
| 23) | Chopper | | |
| 24) | Chopper, Cover | | |
| 25) | Chopper Housing Assembly | | |
| 26) | Screw #4-40 | | |
| 27) | Spacer | | |
| 28) | Grommet | | |
| 29) | Washer, #4 | | |
| 30) | Screw, #4-40 | | |
| 31) | Insulator Pad | | |

3.0 ELECTRONICS SYSTEM AND SIGNAL PROCESSING

3.1 Electronics System

The entire electronics system can be divided into two sub-systems; one system controlling electronics and the other signal processing electronics. The system controlling electronics consists of the temperature controller circuit and the motor speed controller circuit. The signal processing electronics include the analog signal amplifier, synchronous timing signal generator, filter, digital signal processor and the alarm driver (leak indicator) circuit. Except for a link through the power line and the clock signal lines, the two sub-systems are independent of each other as shown in Figure 3.1. The thermo electric (TE) cooler, fan and chopper motor are driven by the 28V power supply directly and the rest of the electronics are powered by a voltage converter which provides $\pm 15V$, $\pm 12V$ and $5V$. For the required 16 bit precision, a separate low noise power supply is used for the ADC board.

3.1.1 Chopper Temperature Controller Circuit

Due to the requirement of the steady and stable correlation gas temperature and the blank sector temperature (less than 0.5K fluctuation as shown in the Phase I Report), a specific design has been employed in the GASPILS sensor. The chopper wheel (which contains the gas cells and blank sectors) is contained in an insulated box and the interior temperature of the box is controlled to maintain a fixed temperature. A pair of thermo electric coolers (Melcor CP1.4-71-06L), an electronic temperature sensor (LM134) and a feedback electronics circuit are employed for this purpose. As shown in Figure 3.2 the current through the TE cooler is driven by a pair of power transistors, and the temperature information picked off by the LM134 is fed back to control the current through the TE cooler. The TE cooler can either cool or heat the box depending on the pre-set temperature and the ambient temperature to maintain the interior temperature of the box at a fixed value.

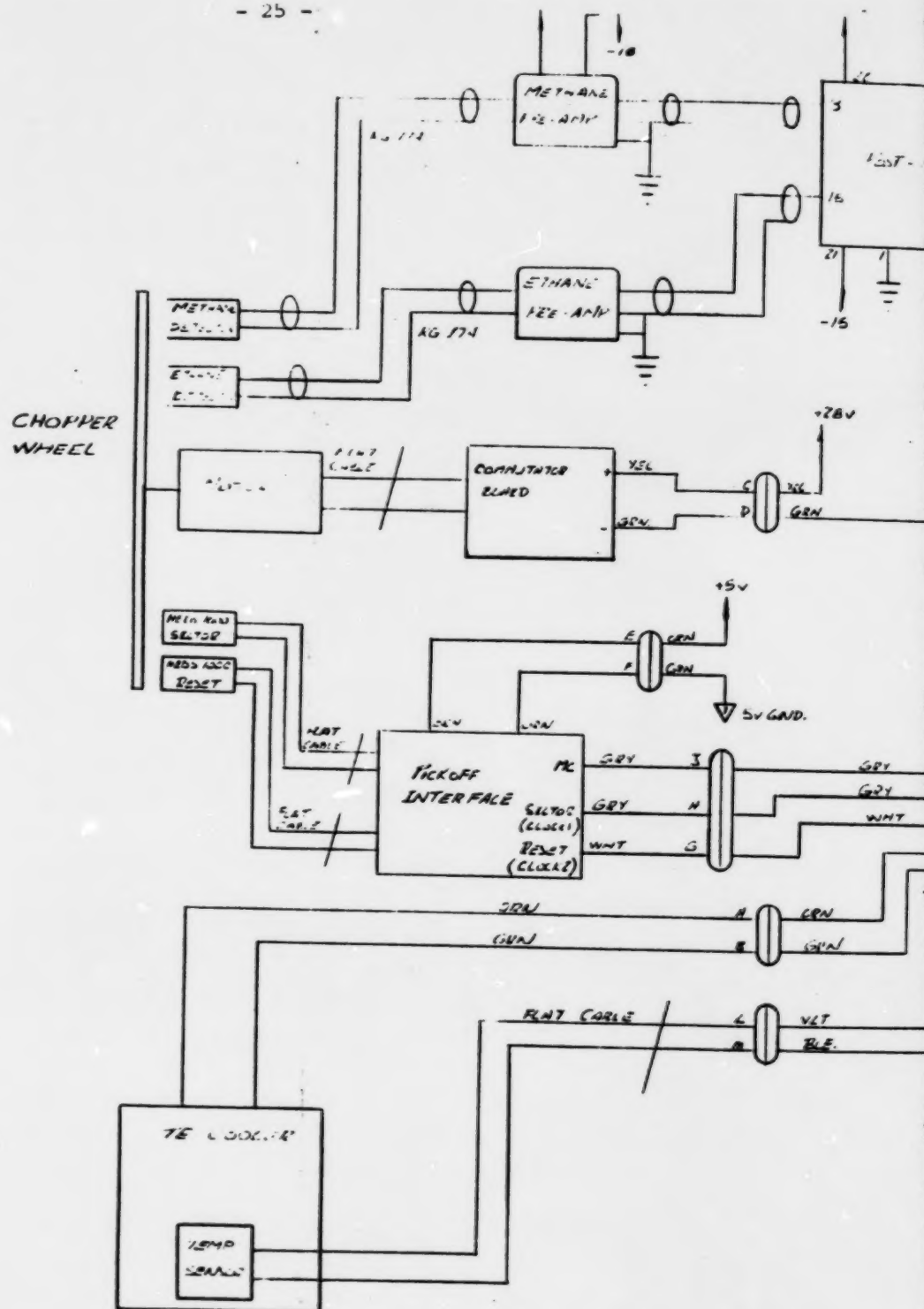


Figure 3.1: GASPILS System Wiring Diagram

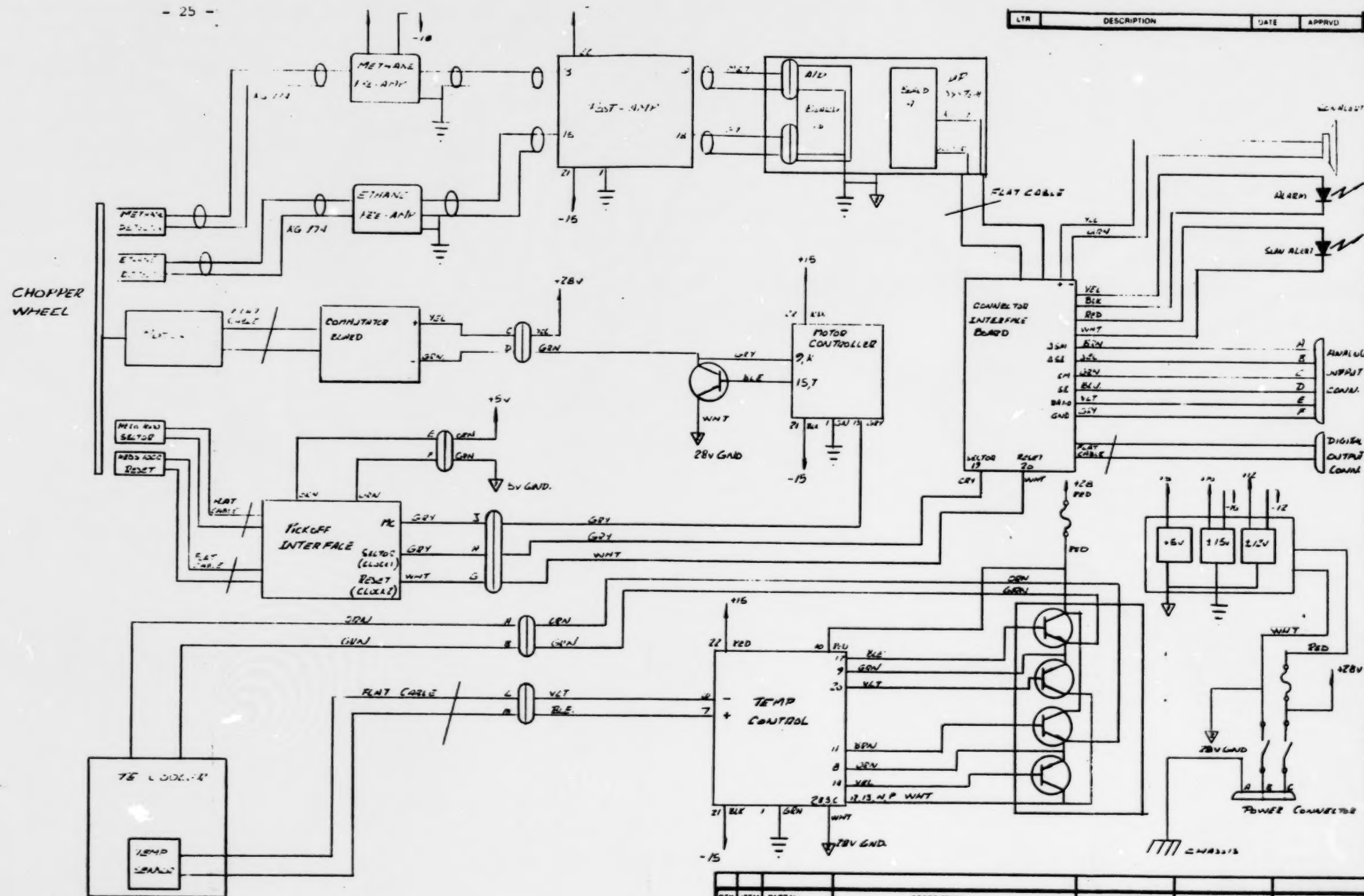


Figure 3.1: GASPILS System Wiring Diagram

QTY	ITEM	PART NO	DESCRIPTION	MATERIAL	HEAT TREATMENT	FINISH
LIST OF MATERIAL						
REQUIREMENTS — UNLESS SPECIFIED			DRAWN	 MONITEQ LTD. 630 RIVERMEDE RD. CONCORD, ONT. L4K 1B6		
GENERAL		LIMITS	CHECKED	DRAWING TITLE		
1 DIMS ARE IN INCHES		1 PARALLELISM ± .0025		GASPILS WIRING DIAGRAM		
2 SURFACE ROUGHNESS 125 ✓ MAX.		2 ECCENTRICITY NOT TO EXCEED .006	APPR.			
3 TOLERANCES ON X = XX = XXX = ANGLES =		3 SYMMETRY ABOUT ALL M/C CENTRE LINES .005	ELECT.			
		DO NOT SCALE DRAWING		SCALE 1/1 WGT GAL ACTUAL REVISION		
NEXT ASSY				DRAWING NO C 1270		
				SHEET 1 of 1		

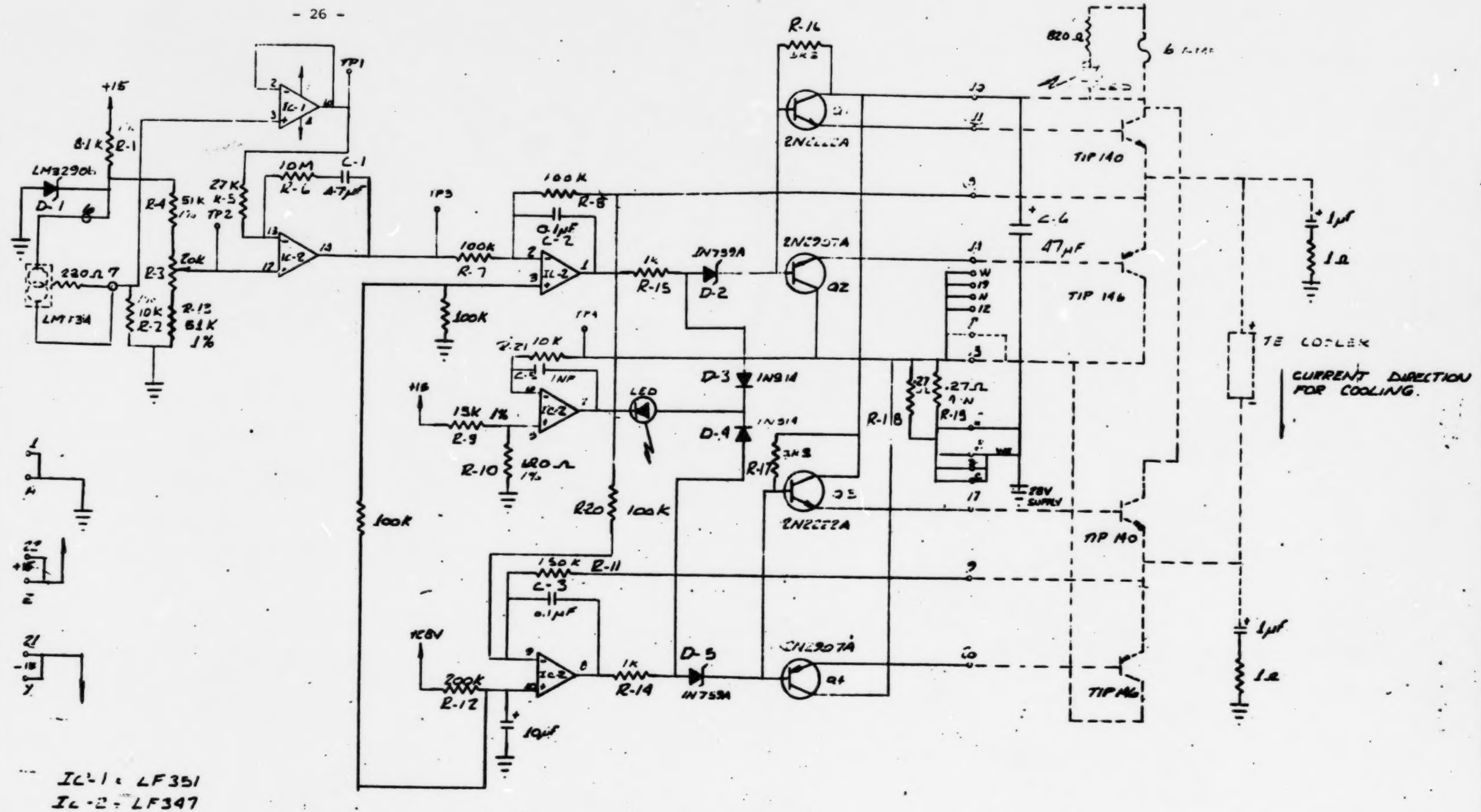
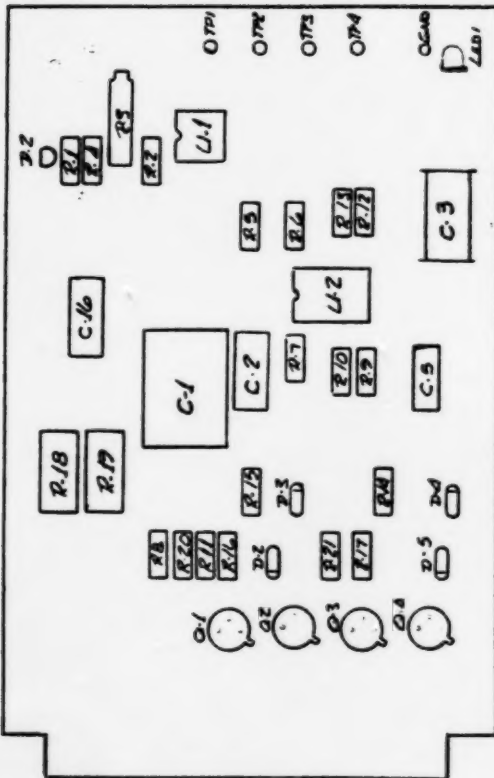


Figure 3.2a: GASPILS T.E. Cooler Electronics
Circuit Diagram

QTY.	ITEM	PART NO.	DESCRIPTION	MATERIAL	HEAT TREATMENT	FINISH
LIST OF MATERIAL						
REQUIREMENTS - UNLESS SPECIFIED				 MONITEQ LTD. 630 RIVERMEDE RD. CONCORD, ONT. L4K 1B6		
GENERAL		LIMITS				
1. DIMS ARE IN INCHES.		1. PARALLELISM ± .005	DRAWN <i>Rev 6 Aug. '88</i>	DRAWING TITLE <i>GASPILS</i> <i>TE. COOLER CONTROLLER</i>		
2. SURFACE FINISHES 125 ✓ MAX		2. SCENTRICITY NOT TO EXCEED .005	CHECKED			
3. TOLERANCES UNLESS H = KX = KXZ = ANGLES =		3. SYMMETRY ABOUT ALL M/C CENTRE LINES .005	APPR.			
			ELECT.			
		DO NOT SCALE DRAWING	NEXT ASSY	SCALE MET. CAL. ACTUAL REVISION		
				SHEET <i>1 of 2</i> DRAWING No. <i>C/1930</i>		



QTY	ITEM	PART NO	DESCRIPTION	MATERIAL	HEAT TREATMENT	FINISH
LIST OF MATERIAL						
REQUIREMENTS - UNLESS SPECIFIED			DRAWN	MATERIAL		
GENERAL			LIMITS	DRAWING TITLE		
1 DIMS ARE IN INCHES			1 PARALLELISM ± .0025	MONITEQ LTD. 630 RIVERMEDE RD CONCORD, ONT L4K 1B0		
2 SURFACE ROUGHNESS			2 ECCENTRICITY NOT TO EXCEED .008	DRAWING NO		
125 ✓ MAX			3 SYMMETRY ABOUT ALL W/C CENTRE LINES 0.05	GAS PILS T.E. COOLER CONT.		
3 TOLERANCES ON				SCALE 1:1		
A =				WGT CAL		
XX =				ACTUAL		
XXX =				DRAWING No		
ANGLES =				REVISION		
			DO NOT SCALE DRAWING	SHEET 2 OF 2		
			NEXT ASSY	C-1930		

Figure 3.2b: GASPILS T.E. Cooler Electronics Circuit Diagram (cont'd)



The output of the LM134 is buffered by follower IC-1 which has an input impedance of 10^{12} ohms. The error amp IC-2D is used to subtract the reference voltage across potentiometer R3 from the temperature sensor potential. System loop response is determined by R6 and C1. IC2A and ICRC together with transistors Q1, 2, 3, and the off board TIP140's and 146's comprise a high current bridge amplifier. The 14 Volts at 6 amps developed with either polarity enables the T.E. cooler to either heat or cool the chopper housing. Current is limited by means of IC2B. When the voltage due to load current in R19 exceeds the reference across R10 the output pin reads negative. This draws both sides of the bridge toward ground, limiting the current and turning on the LED limit indicator.

The large thermal inertia of the temperature controller box stabilizes any short term temperature fluctuations. The temperature of the entire box is stabilized within 20 minutes after power is turned on. The system is designed to obtain the required temperature stability ($\approx 0.5K$) for a temperature difference of less than 10K between the interior and exterior of the box. A test operation shows better than 0.1K stability for the interior temperature 10K below the ambient temperature.

3.1.2 Chopper Speed Controller Circuit

To attain the maximum duty factor and to avoid any problems associated with the irregularity in the synchronous timing signal, derived from the timing marks on the chopper wheels, the chopper wheel rotation frequency is designed to be maintained at a pre-set value within $\pm 1\%$ error. This is accomplished using a miniature electronic DC (brushless) motor (Siemens 1AD 3101-OM) and a motor speed controller circuit, together with an optical reflective sensor viewing the timing marks.

The signal from the timing marks for the sector position (see Figure 1.5) are fed into a power transistor base which controls the current through the

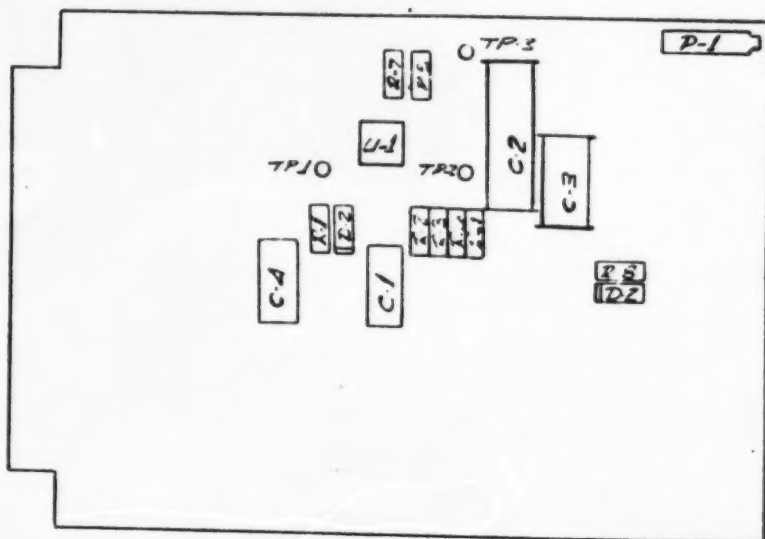
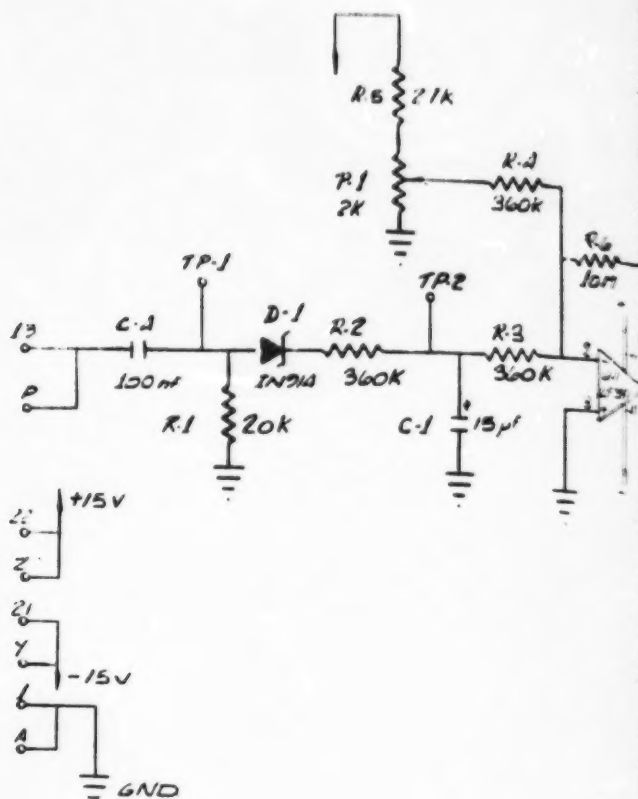
motor commutator. The potentiometer P1 is used to set the desired chopper frequency as shown in Figure 3.3. A constant chopper wheel frequency (0.5% fluctuation) is obtained by this design. This variation in speed does not affect the operation because of the fixed digital sampling rate and number of samples per sector, which is independent of such small variations. The large amount of inertia of the chopper wheel also helps to stabilize the chopper frequency.

The optical reflective sensor is an integrated module (HP HEDS 1000) containing a 700 nm visible LED emitter and a matched IC photodetector (Figure 3.4). A bifurcated aspheric lens is used to image the active area of the emitter and the detector to a single spot 4.34 mm in front of the package. Thus the sensor is sensitive to the distance between the timing mark surface and the detector, as well as the reflectivity of the timing mark. The distance was obtained experimentally by adjusting the sensor position until a reliable and clean timing signal was obtained.

3.1.3 Detector and Amplifiers

The detectors (Infrared Associates Inc. HgCdTe detector) are operated in the high responsivity photoconductive mode (Appendix II). The detector responsivity increases as a function of the bias current, although noise also increases. The D^* (figure of merit), reaches the maximum at a certain bias current and decrease rapidly for an increase in the bias current. Thus, the bias current must be selected to maximize the signal to noise ratio rather than the responsivity. A custom designed matched pre-amplifier which provides the bias current is used on each channel to obtain approximately X 600 gain. The optimum bias current is set by an external resistor. A low thermal coefficient metallic resistor is used to minimize the noise originating from the bias resistance. The pre-amplifier output is further amplified by a post-amplifier (Figure 3.5) to obtain approximately 10V peak to peak





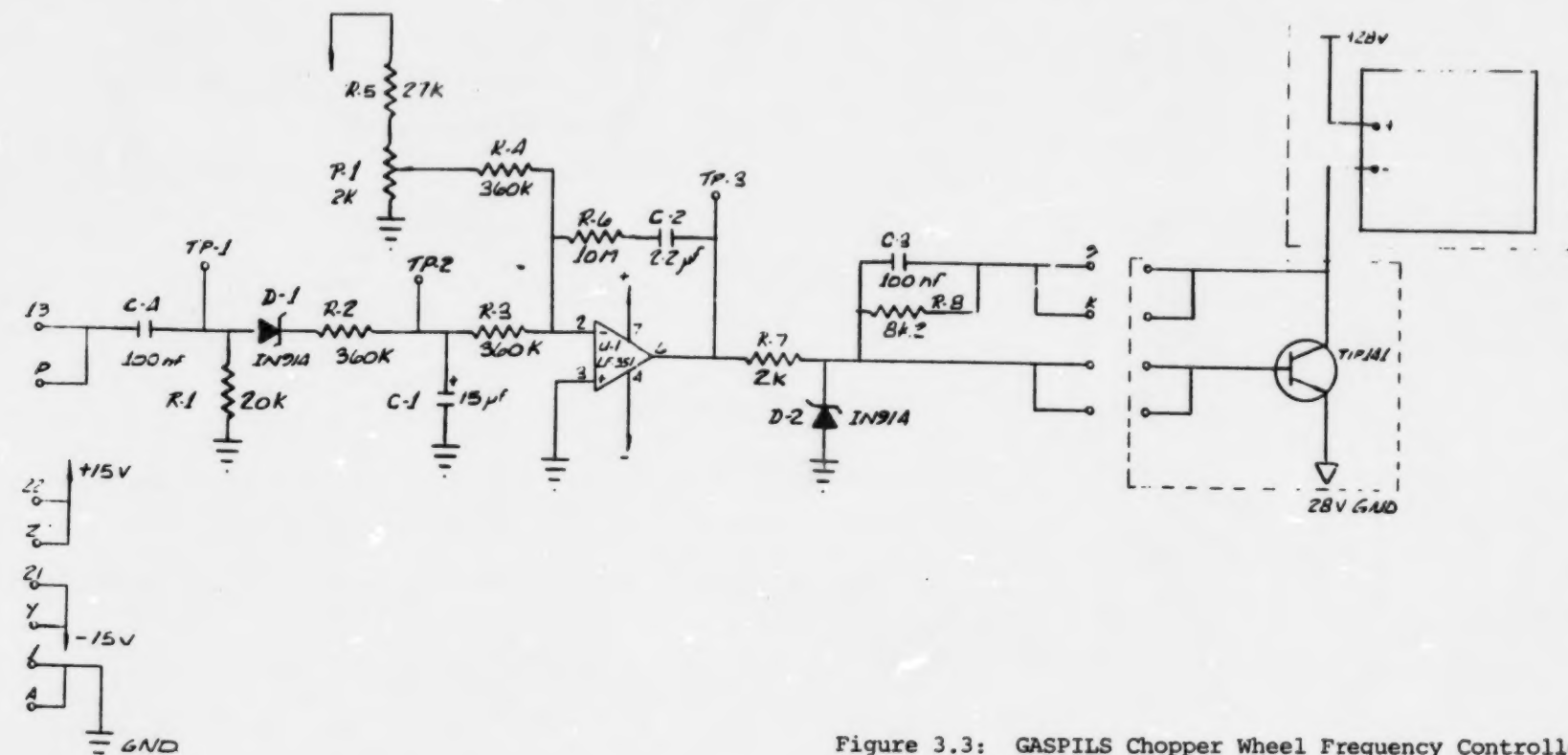
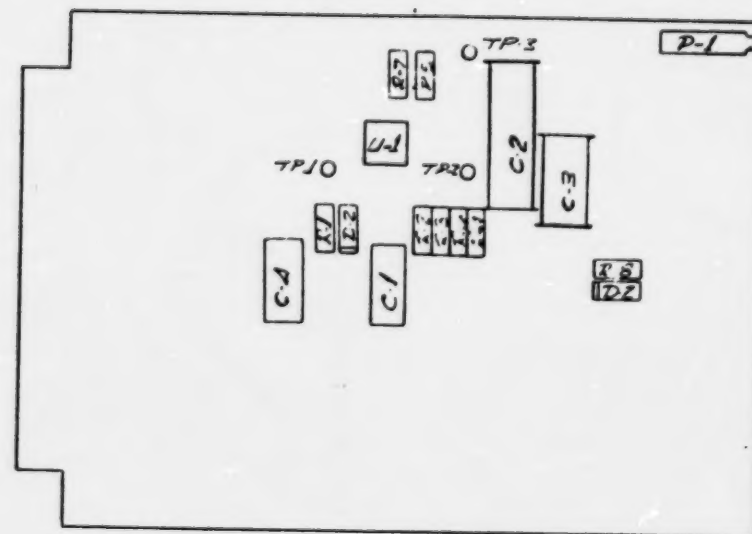
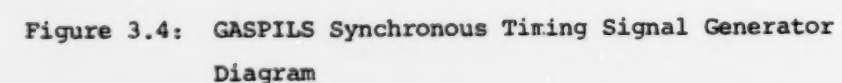


Figure 3.3: GASPILS Chopper Wheel Frequency Controller
Circuit Diagram

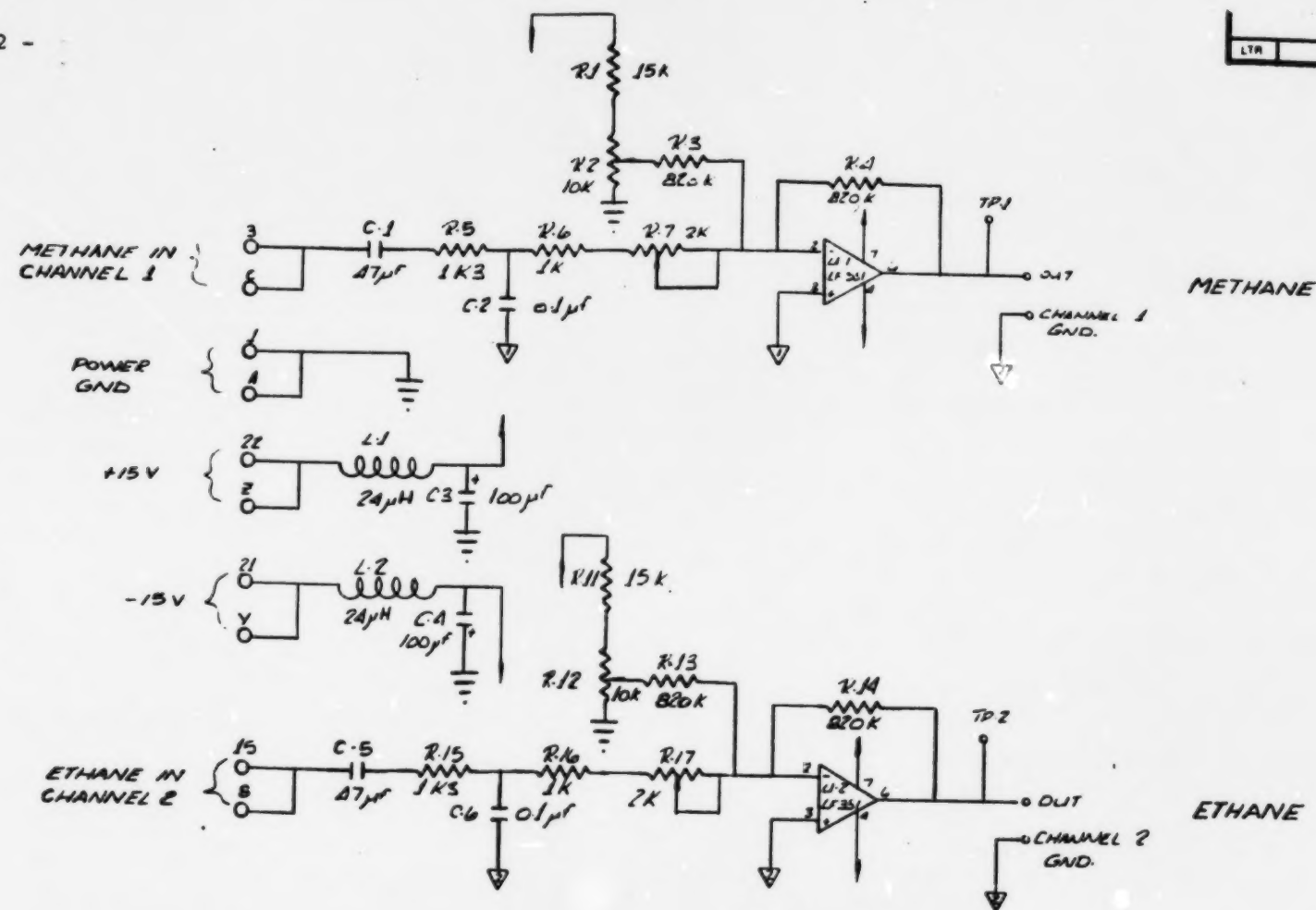


QTY	ITEM	PART No	DESCRIPTION	MATERIAL	HEAT TREATMENT	FINISH
LIST OF MATERIAL						
REQUIREMENTS - UNLESS SPECIFIED			DRAWN	TAM. SAIG & CO.		
GENERAL			CHECKED	MONITEQ LTD.		
LIMITS			APPR.	830 RIVERMEDE RD. CONCORD, ONT. L4K 1B6		
1 DIMS ARE IN INCHES			ELECT.	DRAWING TITLE		
2 SURFACE ROUGHNESS				GASPILS		
125 ✓ MAX				MOTOR CONTROLLER		
3 TOLERANCES ON				SCALE 1/1		
X =				WGT. COL. ACTUAL REVISION		
XX =				DRAWING No C1928		
XXX =				SHEET 1 OF 1		
ANGLES =				NEXT ASSY		
DO NOT SCALE DRAWING						

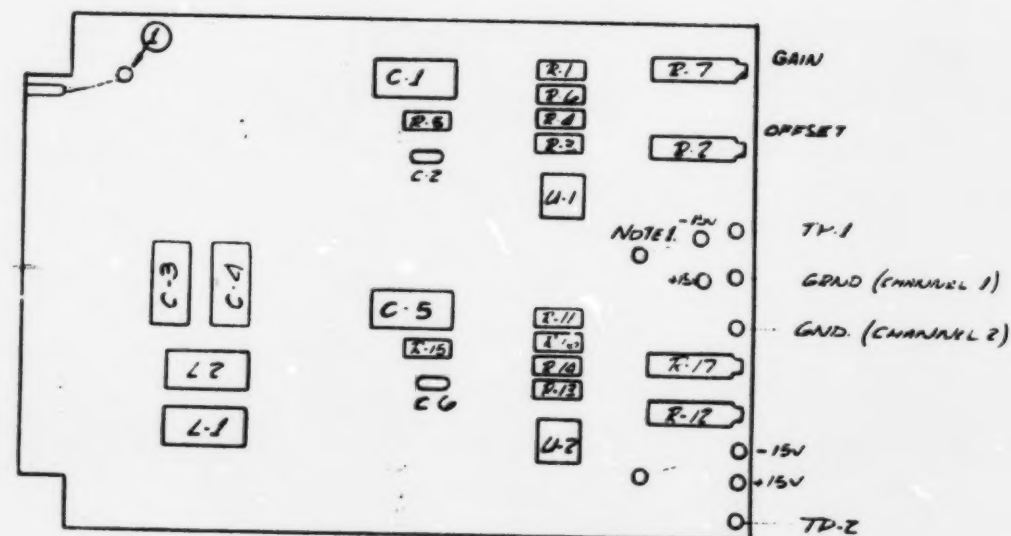


NOTE:-
1) U-1 is 14093
2) U-2 & 3 is NEDS-1000

QTY	ITEM	PART No.	DESCRIPTION	MATERIAL	HEAT TREATMENT	FINISH
LIST OF MATERIAL						
REQUIREMENTS — UNLESS SPECIFIED			DRAWN	 MONITEO LTD. 630 RIVERMEDE RD CONCORD, ONT. L4K 1P		
GENERAL		LIMITS	CHECKED	DRAWING TITLE GASPILS PICK-OFF INTERFACE		
1 DIMS ARE IN INCHES		1 PARALLELISM ± .0025				
2 SURFACE ROUGHNESS 125 ✓ MAX.		2 ECCENTRICITY NOT TO EXCEED .005				
3 TOLERANCES ON X = XX = XXX = ANGLES =		3 SYMMETRY ABOUT ALL M/C CENTRE LINES .005				
		DO NOT SCALE DRAWING	ELECT.	SCALE 1:1 SHEET 1 OF 1 WGT CAL ACTUAL REVISION DRAWING No C-1929		
			NEXT ASSY			



REVISIONS			
LTR	DESCRIPTION	DATE	APPRVD



NOTE 1) OFFSET POLARITY IS POSITIVE IF JUMPER IS CONNECTED TO -15V (NEGATIVE IF +15V)

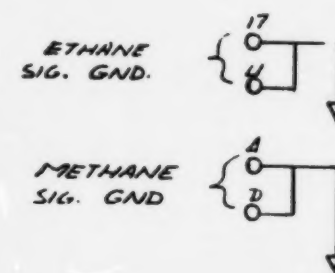


Figure 3.5: GASPILS Post-amp circuit diagram

QTY	ITEM	PART NO	DESCRIPTION	MATERIAL	HEAT TREATMENT	FINISH
LIST OF MATERIAL						
REQUIREMENTS - UNLESS SPECIFIED						
GENERAL			LIMITS	DRAWN	TAM 5 A 16 '82	
1 DIMS ARE IN INCHES			1 PARALLELISM	CHECKED		
2 SURFACE ROUGHNESS			2 SCENTRICITY	APPR.		
125 ✓ MAX			NOT TO EXCEED 005	ELECT.		
3 TOLERANCES ON			ALL M/C CENTRE LINES			
X.0			DO NOT SCALE			
XX.0			DRAWING			
XXX.0						
ANGLES						
DRAWING TITLE				SCALE	1:1	ACTUAL
GASPILS POST-AMP.				SHEET	1 OF 1	REVISION
DRAWING NO				C1227		

amplitude. The post-amplifier also provides the d-c level at the output for a unipolar 10V amplitude modulating signal. Since the modulation amplitude must not exceed the ADC range (10V), the post-amplifier gain factor will have to be adjusted to fit the field operational condition.

3.1.4 Digital Signal Processing Electronics

The signal from the post-amplifier is first filtered by a low-pass filter circuit before the digital signal processing electronics.

The signal processor consists of a digital hardware unit which processes the radiance signals from the detector-amplifier to determine the methane and ethane gas signals and the ratio signal. The Z-80 micro-processor carries out the required calculation (16 bit accuracy) in real time and outputs two radiance signals, two gas signals and the ratio signal in analog form as well as in digital form. The processor furthermore activates audio and visual alarms (gas leak indicator) when the ratio signal exceeds a certain threshold value which is pre-set manually.

Details of the hardware and specifications of the digital signal processing electronics are discussed further in Appendix I.

3.2 Signal Processing

The schematics of the radiance signals from the detector-amplifier is shown in Figure 2.2 along with the two TTL clock signals. The radiance signals, after the low pass filter, is then sampled and digitized 128 times during each sector period, and averaged. These average values for each sector in both channels are fed to the microprocessor as is indicated in the following paragraphs.

The radiance signals are multiplied by the zero gas balance factors (refer to the Phase I Report) to obtain the new radiance signals as:

$$\begin{aligned} GM'_j &= GM_j & GE'_j &= GE_j \\ RM'_j &= RM_j \times gm_1 & RE'_j &= RE_j \times ge_1 \\ BM'_j &= BM_j \times gm_2 & BE'_j &= BE_j \times ge_2 \end{aligned}$$

Gm and ge's are manually controllable 16 bit numbers, G and R are the radiance signals through the correlation gas cell and the reference cell respectively and B is the radiance signal from the blank sector. M and E indicate the methane and ethane channel respectively. The G and R values of the methane channel are interpolated at the B sector position to compensate for linear variations as follows:

$$GM''_j = 1/3 (GM'_j + 2GM'_{j+1}) \quad , \quad RM''_j = 1/3 (2RM'_j + RM'_{j+1})$$

Similarly, the G and B values of the ethane channel are interpolated at the R sector position as:

$$GE''_j = 1/3 (GE'_j + 2GE'_{j+1}) \quad , \quad BE''_j = 1/3 (2BE'_j + BE'_{j+1})$$

The scene radiance signals S's, and the gas signals, ΔS's are computed using the balanced and interpolated radiance signals as:

$$\begin{aligned} SM_j &= GM''_j - BM'_j & SE_j &= GE''_j - BE''_j \\ \Delta SM_j &= GM''_j - RM''_j - BM'_j & \Delta SE_j &= GE''_j - RE'_j - BE''_j \end{aligned}$$

The S signal is the differential radiance of the ground with respect to the blank sector radiance and the ΔS signal is due to the leak gas present between the ground and the sensor. Notice the S signals uses G signal rather than the R to make it insensitive to the presence of leak gas. Since the blank sector temperature is constant, the variation in S represents the variation in the ground radiance.

The S and ΔS are averaged for selectable samples, and the ratio signal is calculated using the averaged gas signals. The signals at the output port of the sensor consist of:

$$\overline{SM}, \overline{SE}, \overline{\Delta SM}, \overline{\Delta SE} \text{ and } R = \overline{\Delta SE} / \overline{\Delta SM}$$

The processor also activates the audio and visual alarm when the ratio signal ($\equiv$ gas leak signal) becomes higher than a pre-set threshold value. The threshold value is manually settable by using a provided 8 bit dip switch. An LED indicator is also employed to indicate the possible D/A overflow in the ΔS associated with the extremely large gas leak.

3.3 Output and System Adjustment

The analog signals are fed out at the multipin Bendix connector. The outputs are assigned to the pin as follows:

Signal	Pin #
$\overline{SM}$	C
$\overline{SE}$	D
$\overline{\Delta SM}$	A
$\overline{\Delta SE}$	B
R	E
GND	F



The digital output is provided at the T_2 connector on the control panel. The output consists of 7 bit ASC-11 characters fed out at 300 baud rate on RS-232 interface. The sequence of the data is as follows:

Carriage Return
Line Feed
 $\overline{\Delta SM}$ $\overline{\Delta SE}$ $\overline{SM}$ $\overline{SE}$ R

System adjustments and operation is required in the initial system set up to ensure the proper performance of the sensor. These include the various setting on the electronics as well as opto-mechanical adjustments. The settings for the electronic system are listed below:

- i) Sampling period and the delay time selection using the dip switch provided on board #4. The sampling period and the delay time must be set so that the sampling period and delay time can be entirely contained in the sector period. The integration time is related to the dip switch setting, τ_s , as

$$\tau = 256 \times \frac{\tau_{s+1}}{4} \mu s$$

and the delay time is related to the dip switch setting, D_s , as

$$D = D_s \times \frac{\tau_{s+1}}{4} \mu s$$

The final decision on the τ and D must be made to obtain the maximum sensor duty factor. Note that the value of $\tau + D$ cannot be smaller than 12 msec due to the 16 bit ADC1140 requirement. This ADC takes 35 μsec for 1 data point and 7 μsec is required for the S/H and the multiplexer. The master clock is stable to 100 ppm, which is more than sufficient in the GASPIIS application.

- ii) Chopper speed selection - the chopper speed must be selected considering the aircraft speed and the stability of the chopper wheel. 2000 rpm has been shown to be the proper speed. When the chopper speed is selected at a different value, the τ and D in (i) must be re-adjusted.
- iii) Chopper wheel-gas cell temperature setting - the chopper wheel-gas cell temperature is set by adjusting the setpoint potentiometer on the temperature controller board. Approximately 5K above the average atmospheric temperature is recommended for the chopper temperature setting. This way the temperature controller will operate properly for $\pm 15K$ ambient temperature variations.
- iv) Zero gas balance adjustment - Zero gas balance is adjusted to ensure that the variation in the incoming radiance will not give false gas signals. The balance for the correlation cell transmittance is obtained by using a variable blackbody radiation source. In the absence of the test gas, the radiation source temperature must not give any gas signal for the correct balance value. This balance value should give a gas signal insensitive to the incoming radiance change.



4.0 GASPILS LABORATORY PERFORMANCE TEST AND GAS DETECTION SENSITIVITY CALIBRATION

The GASPILS performance was tested in a laboratory using a variable temperature blackbody source and a large test gas cell made of 12.5 cm diameter and 61 cm high pyrex cylinder and a thin vinyl foil window. The scene radiance variation was simulated by changing the blackbody source temperature and the test gas optical thickness was varied by injecting known amounts of the gas into the cylinder using a syringe. The test gas was contained in the test gas cell for a long time due to the low diffusion velocity of the test gas in the atmosphere.

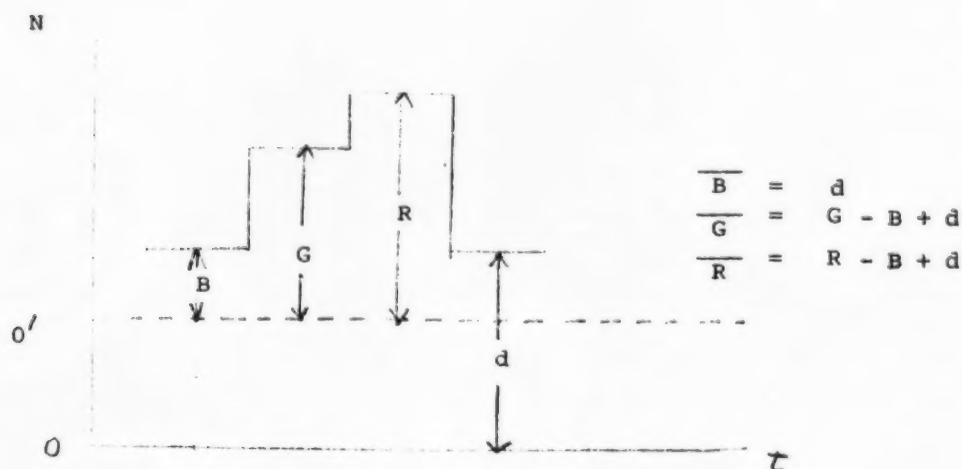
4.1 Infrared Radiance Measurement: Principle and Practice

Unlike the visible and ultraviolet radiation, infrared radiation originates from a low temperature source with a significant radiation power. To measure the true radiance of a source one must measure the difference of radiance between the source and a very low temperature ($\sim 0^\circ\text{K}$) reference source, which is not readily achieved.

However, GASPILS does not require a true radiance measurement since the difference radiance due to the presence of the target gas is the only relevant quantity. A constant temperature source (blank sector) is, therefore, used in GASPILS as a reference source and the radiance signals from each of the sectors, including the gas cell, reference cell and the blank sector, are measured from this arbitrary blank reference and these signals are processed to extract the gas signal.

The relationship between the true radiance signal and the measured radiance signal and its impact on the gas signal is discussed as follows.

The true radiance (barred quantity) from each of the sectors can be written as a sum of the difference radiance and an offset value as depicted in the following diagram:



Here B, G and R are the measured electric signal corresponding to the blank, reference cell, and gas cell sector, respectively and the value d is the constant.

To obtain the zero gas balance, the true radiance signals, $\overline{G}$ and $\overline{R}$ must be used. The gas signal, ΔS , is written as

$$\begin{aligned}\Delta S &= \overline{G} - g_1 \overline{R} - g_2 \overline{B} \\ &= (G - B + d) - g_1 (R - B + d) - g_2 d \\ &= G - g_1 R - (1 - g_1)B + (1 - g_1 - g_2)d\end{aligned}\tag{4.1}$$

The last term in (4.1) is a constant which does not have any impact on the gas measurement. Therefore by setting the correct electronic gain

factors on the reference signal and blank signal, the GASPILS zero gas balance can be obtained so that the source radiance variation will not have any impact on the gas signal in the absence of the target gas.

The zero gas balance of the GASPILS is obtained by using a variable temperature blackbody source and a set of 16-bit dip-switches provided on one of the digital electronics boards. The measured zero gas signal and the radiance signal with correct balancing, is shown in Figure 4.1, for a temperature variation of 9°C . The zero gas balance holds for a wide range of the source temperature variation (20° variation has been tested and demonstrated). In practice, however, more than 15° variation is not anticipated in the field. For larger dynamic range, the dynamic range of the sensor can be re-adjusted by reducing the gain factors of the amplifier. The balance still remains good for different gain factors and offset values provided the chopper temperature is maintained constant. (See Figure 4.2).

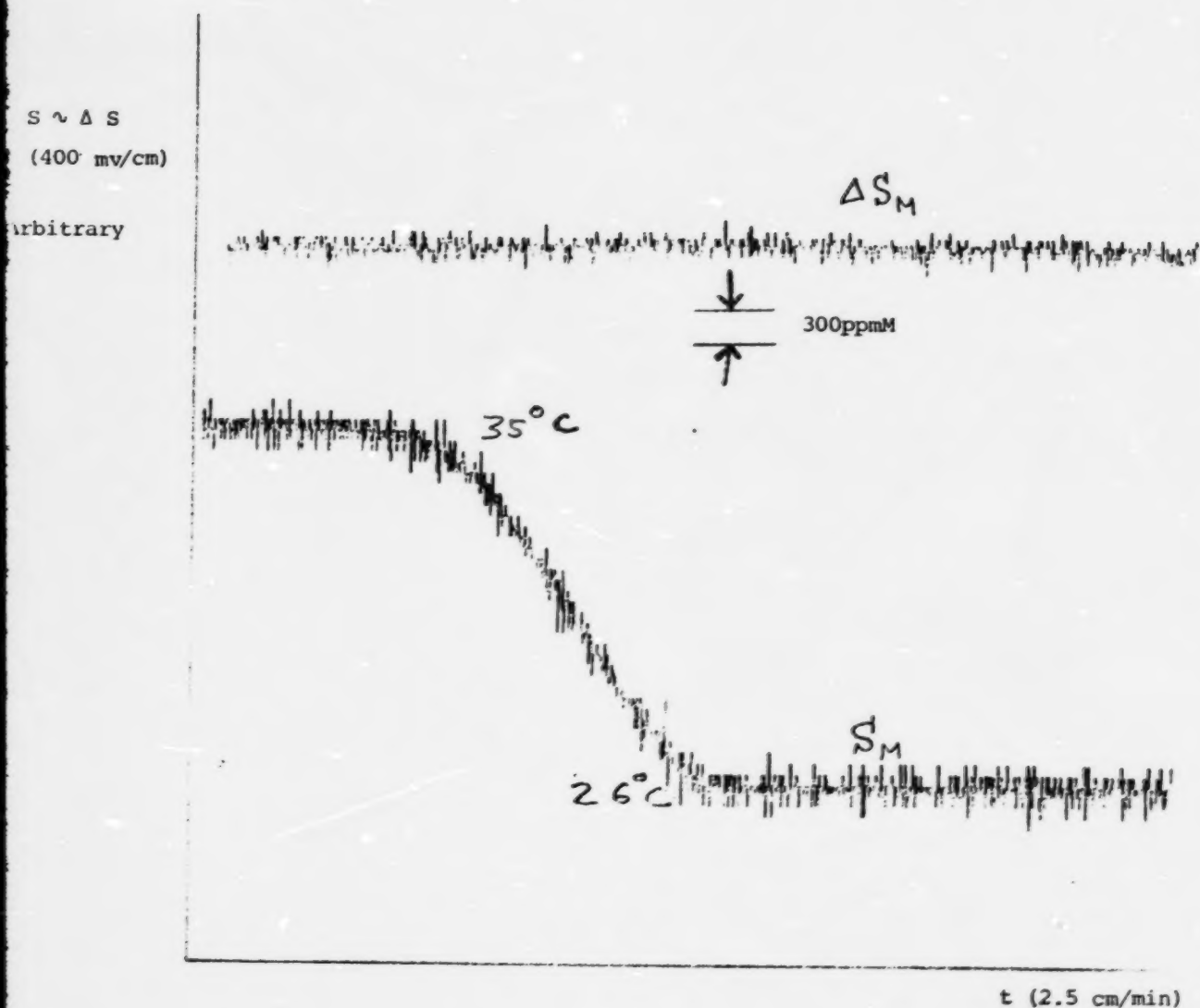


Figure 4.1: The stability of the zero gas signal of the methane channel for the source temperature variation;
S-radiance signal, ΔS - gas signal.

ΔS
(400 mv/cm)

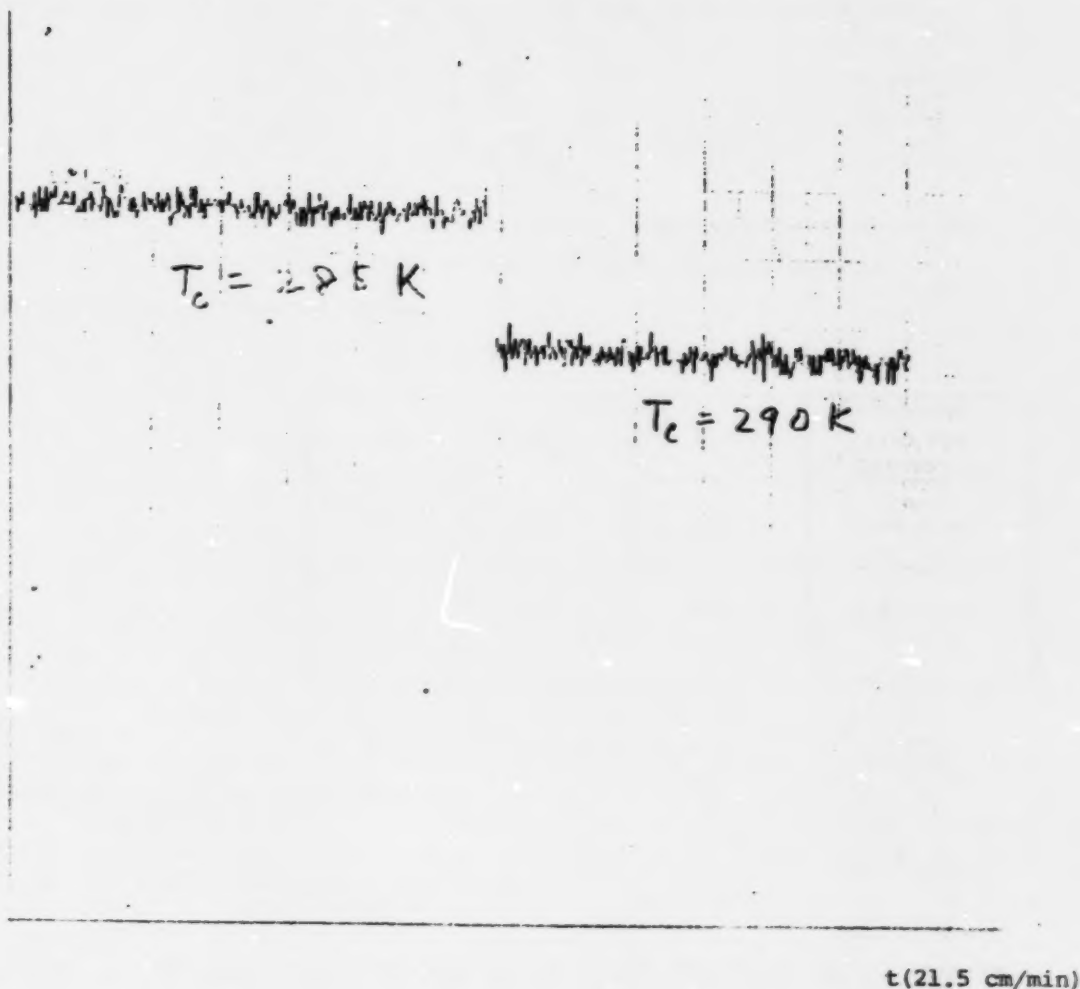


Figure 4.2: Change in the zero gas signal of the methane due to the chopper temperature change.

4.2 System Responsivity and FOV Measurement

The output radiance signal, V_s , is related to the radiance power, Pr , as

$$V_s = A_2 \cdot A_1 \cdot Rd \cdot Pr$$

Where A_1 and A_2 are the gains of the pre and post-amplifier and Rd is the detector responsivity. The values of A 's and Rd 's used in GASPILS are listed in the following tables.

	A_2	A_1	$Rd (v/w)$	Estimated $Pr (W)$ for 10° difference
CH_4	49	580	722	6.96×10^{-7}
C_2H_6	47	631	850	4.40×10^{-7}

The radiation power is calculated as:

$$Pr = N(\lambda) \cdot \Delta\lambda \cdot A \cdot d\Omega \cdot T \cdot f(\Delta T)$$

where $N(\lambda)$ is the radiance, $\Delta\lambda$ is the filter bandwidth, $A \cdot d\Omega$ is the etendue, T is the total system transmission coefficient and $f(\Delta T)$ is the fractional change in the radiance due to the temperature difference ΔT and values of these quantities are estimated as follows:

$$\begin{aligned} N\lambda (30^\circ C, 7.8\mu) &= 8 \times 10^{-4} \text{ w/cm}^2 \cdot \text{Sr}\mu \\ N\lambda (30^\circ C, 12.2\mu) &= 8.3 \times 10^{-4} \text{ w/cm}^2 \cdot \text{Sr}\mu \\ \Delta\lambda_M &= 0.294 \mu \\ \Delta\lambda_E &= 0.307 \mu \\ T_M &= T_1 \cdot T_w \cdot T_f = 0.73 \times 0.55 \times 0.5 = 0.20 \\ T_E &= T_1 \cdot T_w \cdot T_f = 0.73 \times 0.50 \times 0.5 = 0.18 \end{aligned}$$



$$Ad\Omega = 7.4 \times 10^{-2} \text{ cm}^2 \text{ Sr}$$

$$f_M(\Delta T = 10K) = \frac{h\nu}{kT} \cdot \frac{\Delta T}{T} = \frac{0.159}{0.026} \times \frac{10}{300} = 0.20$$

$$f_E(\Delta T = 10K) = \frac{0.1}{0.26} \times \frac{10}{300} = 0.13$$

Therefore, the electric signal at the end of the post-amplifier is estimated to be:

$$V_m = 49 \times 587 \times 722 \times 6.96 \times 10^{-7} = 14.4 \text{ Volts}$$

$$V_E = 47 \times 631 \times 850 \times 4.40 \times 10^{-7} = 11.1 \text{ Volts}$$

Due to the 80% gas transmittance and the amplifier roll-off, (Refer to the wave form on the Operations manual - 20 ms decay time for the Methane channel and 30 ms decay time for the Ethane channel) the signal is further attenuated by a factor of 0.48 on the methane channel and 0.64 on the ethane channel to give the following expected values.

$$V_{SM} = 6.9V$$

$$V_{SE} = 7.1V$$

The value of S signal (which is not exactly the same quantity as V_s) is measured at the RS 232 output (See Table 4.1), to give

$$S_M = 12282 \text{ count for } 30^\circ\text{C}$$

$$S_M = 17488 \text{ count for } 40^\circ\text{C}$$

AND

$$S_E = 11008 \text{ count for } 30^\circ\text{C}$$

$$S_E = 14336 \text{ count for } 40^\circ\text{C}$$

Here it is important to note that the quantity S is not equal to G-B but is equal to $G - (1-g_1)B$, and the signal is a/c coupled. Due to this fact $S_M(40^\circ\text{C}) - S_M(30^\circ\text{C})$ does not represent the true radiance change for 10°C difference as depicted in the following diagram.

$\Delta S_M \Delta S_E S_M S_E R$

-07E0-0290+301F+29C5+5758
 -082F-02AA+303B+2720+53EB
 -083F-02C2+3044+2F2A+562E
 -07C7-02C2+304F+2B24+59A1
 -0846-02B6+2FF8+2967+540A
 -0857-02C3+3001+3063+54EC
 -0844-02BF+3036+29C3+5521
 -0842-02AD+3009+2C88+52F3
 -0855-02C1+3010+27EF+540E
 -082B-02C1+3059+2F0C+56BF
 -081C-02A2+304D+22CA+5397
 -082A-02CC+2FF0+2D90+581A
 -07FA-02AB+3066+2B99+560A
 -0820-02A4+307F+2B60+532F

$T_S = 30^\circ\text{C}$

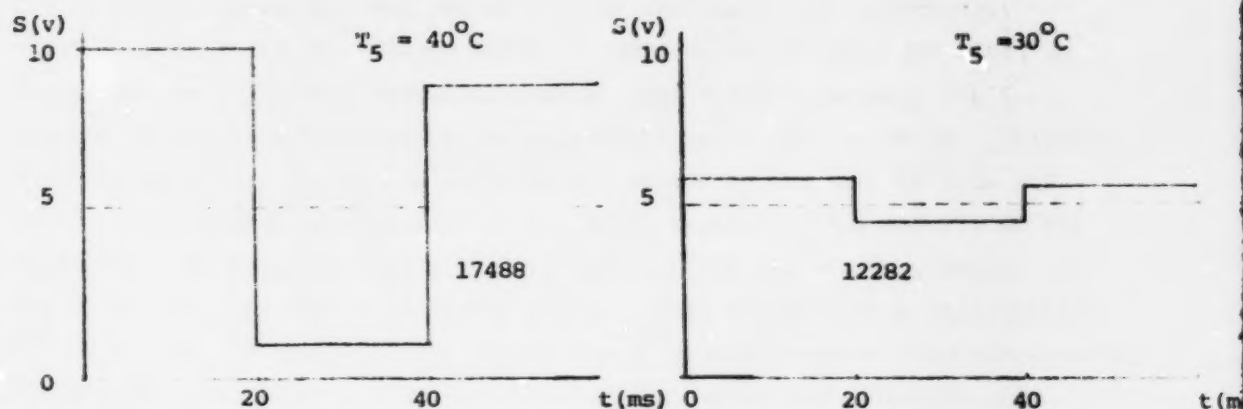
$\Delta S_M \Delta S_E S_M S_E R$

-0825-02E0+43D9+372F+5A90
 -07BC-029D+442E+3823+5B0C
 -081B-02CC+43EE+3803+58CD
 -07F8-02CA+4431+33AD+59F2
 -0805-02CA+4451+3946+5940
 -0805-02E1+441D+3AA4+5C20
 -081F-02C6+4425+3623+580E
 -07FF-02DA+43ED+3862+5875
 -0806-02D9+4467+3ACE+5B20
 -07E4-02C7+4424+36FA+5A43
 -07DB-02CC+445B+3913+5B99
 -0810-02D0+4427+3862+5940
 -0817-02D7+442C+3544+5A2A
 -07DF-02D5+444E+3A7F+5C8F

$T_S = 40^\circ\text{C}$

Table 4.1 : RS232 output for two different source temperatures





However, the true radiance change can be estimated by adding approximately 0.85 volts to the charge in S $[S_M(40^\circ C) - S_M(30^\circ C)]$.

The counts are converted to the voltage using the calibration factor of 2^{15} counts/10 Volts and V_s (refer to Appendix I), is calculated from this measurement to give

$$V_{SM} = 5.5V \text{ and } V_{SE} = 4.9V$$

These values are also cross checked by reading the radiance signal change between $30^\circ C$ and $40^\circ C$ source temperature directly from the oscilloscope trace. These measured values count for 80% of the estimated value on the methane channel and 70% on the ethane channel. The difference in the estimated and measured responsivity may be accounted for in terms of the diffused image quality at the detector area which is unavoidable in the extremely fast optics design (F/0.5). Nevertheless, considering that the main objectives of the optics design are not the image quality but the light gathering power, the 80% efficiency obtained in the GASPILS design should be considered as extremely good performance.

The GASPILS field of view is designed to be 8° to optimize the spatial resolution and the sensor-sensitivity. To assess the designed feature of the

FOV, a simple experiment was set up and carried out in the laboratory. A hot soldering tip was located behind a curtain, which has a 5mm slot, to represent 5mm x 5mm size radiation source. The distance between the field lens of the sensor and the radiation source was maintained at 80 cm. Starting from the left end, the source position was varied by the step of 1 cm and the S signal output was recorded on the chart recorder. The results of the experiment are shown in Figure 4.3 for both methane and ethane channel. The 8° FOV is also indicated in the figure. Both channels show well defined 8° FOV's with flat responsivity across the 4° centre regions. The responsivity falls to zero at 4° from the optic axis on both sides and maintains good symmetry.

4.3 Optimization of the Correlation Coefficient

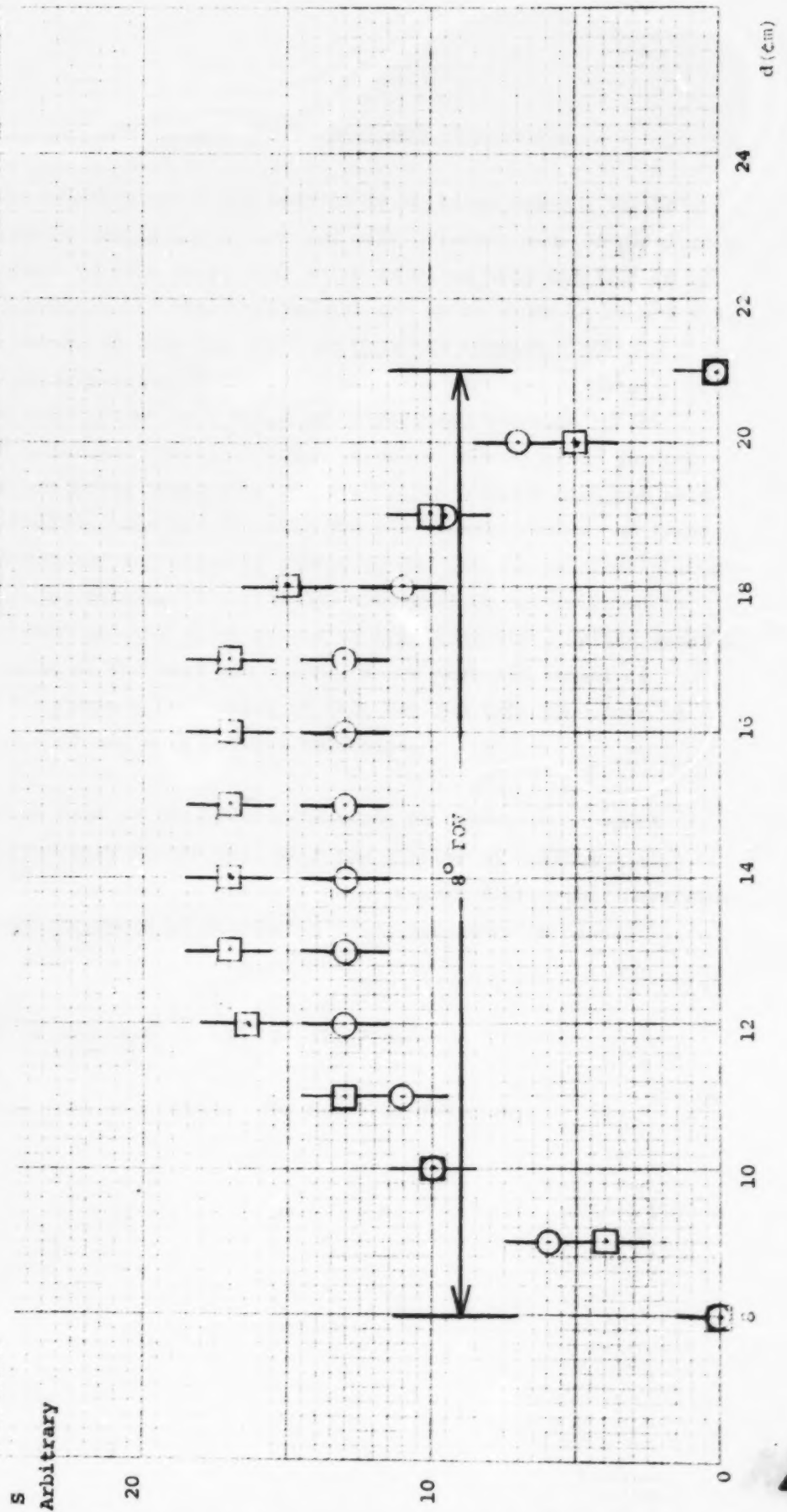
The gas filter correlation technique has high sensitivity and specificity. However, this high sensitivity can only be obtained when the design is optimized, and the experimental data required for this optimization is sometimes unavailable. One of the most important and difficult problems is the correlation gas optical thickness optimization. The optical thickness can be optimized either by computer modelling using the available data or by an experiment. We have taken two different approaches for two different channels; modelling for the CH_4 channel and direct experiment in the C_2H_6 channel mainly because the data for C_2H_6 is not readily available. We have implemented 1 cm. 1 atm. correlation gas cell for both CH_4 , C_2H_6 channel to obtain the Phase 1 predicted optimum performance in CH_4 channel but not necessarily so for the C_2H_6 channel. Preliminary experimentation and estimation indicates that approximately 4 atm.cm correlation gas cell is required for the C_2H_6 channel to obtain optimum sensitivity. To obtain the required optical thickness, the chopper wheel including the gas cell and the temperature controller box need to be reassembled.

Figure 4.3:

The radiance (S) channel output from both Methane and Ethane channels.

A small source (5 mm x 5 mm) has been located at various points on a line 80 cm below the field lens. The designed 8° FOV is also indicated.

□ Methane Channel
○ Ethane Channel



4.4 Gas Detection Sensitivity Measurement and Calibration

The gas detection sensitivity of the GASPILS is measured using a variable temperature blackbody source and a test gas cell cylinder made of plexiglass covered with a piece of thin vinyl foil which is 61 cm high and 12.5 cm diameter. The schematics of the experimental set up is shown in Figure 4.4. Precisely known amount of test gas (CH_4) is injected through a port provided at the lower portion of the cylinder. The test gas diffuses with a diffusion coefficient of $D = 0.2 \text{ cm}^2 / \text{sec}$, and migrates to the top. Due to the relatively fast diffusion velocity, the injected gas can be assumed to be uniformly mixed with the air within a short time and this is verified by observing the gas signal. The gas signal reaches the final value as soon as the gas injection is completed and remains constant throughout calibration. The sealing of the window test cell is not critical in light of low gas leak and the short period of the experiment. After several minutes at one value of the test gas volume, a new measured amount of test gas is added to form a new volume of test gas and this procedure is repeated to build more and more optical thickness.

The test gas volume used in this measurement can be converted to ppm.m values using the geometry of the cell with the premise of uniform mixing of the gas with air, apparent in the test data (Figure 4.5). The conversion factor of 1 cc. gas to ppm.m is calculated using the cross sectional area of the test cell

$$A = \pi r^2 = \pi \left(\frac{12.5}{2} \right)^2 \text{ cm}^2 = 122.7 \text{ cm}^2$$

One cc of gas will form 82.2 ppm.M. The measured gas signal,



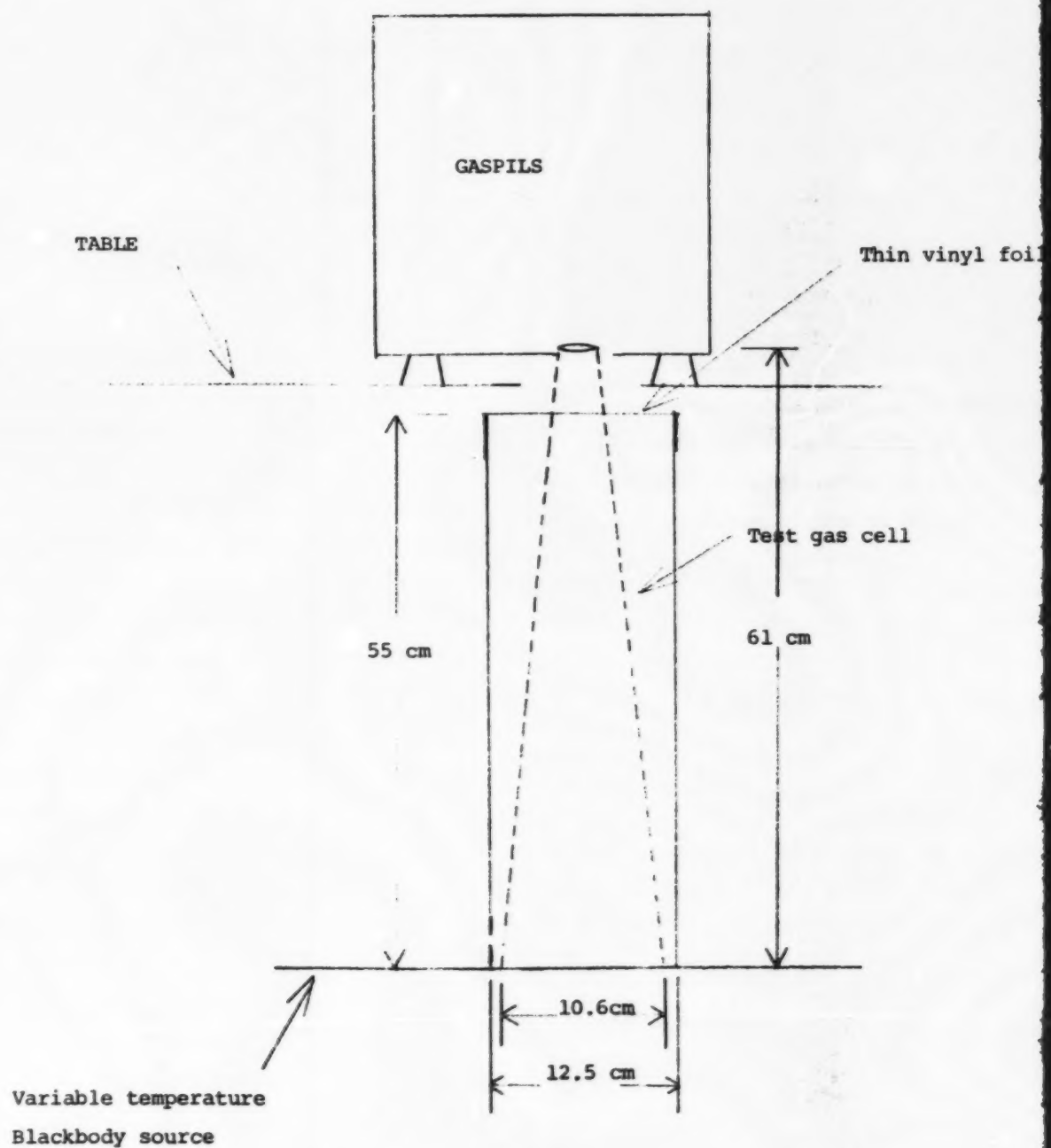


Figure 4.4: Schematics of the GASPILS Sensitivity Calibration Experiment Set-Up

T_s (source temperature) =
34°C

T_g (gas temperature) =
26°C

T_c (chopper temperature) =
285.6°K

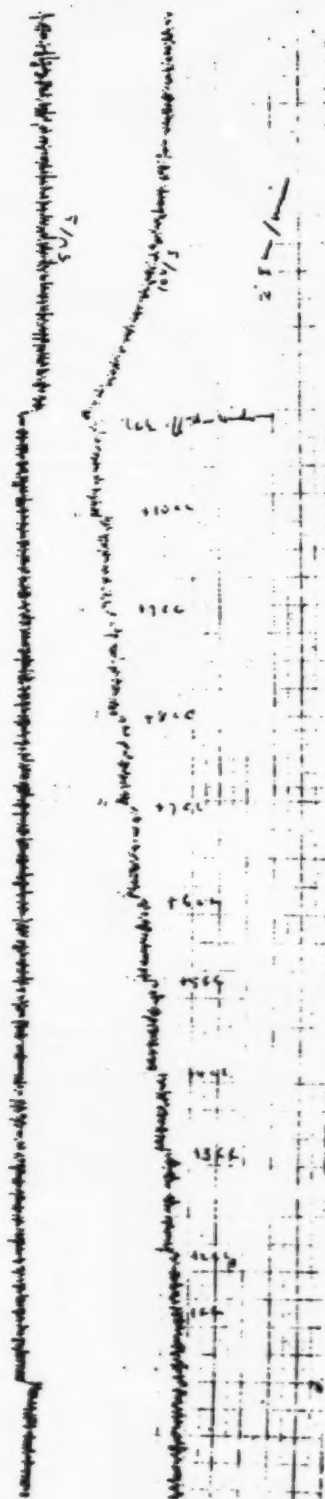


Figure 4.5:

Raw methane gas detection sensitivity calibration data for the CH₄ channel: Upper trace is S and bottom trace is the ΔS signal

ΔS , plotted as a function of the test gas thickness (ppm.M atm) in Figure 4.6 and the r.m.s. noise of the signal is indicated on the same graph.

Notice that the ΔS signal deviates from the linear behaviour as a function of the optical thickness as is indicated in the Phase I report. This feature originates from the test gas spectral line shape change due to the increased optical thickness and deterioration of the correlation coefficient.

This experiment is repeated for various source temperatures and the detection limit, determined by the r.m.s. noise, is obtained and plotted as a function of the source temperature and the gas temperature.

As pointed out in the Phase I report, the field condition is estimated to have an effective temperature difference of 4°C between the source and the target gas. Therefore, the gas detection limit in the field is estimated to be approximately 70 ppm.M as seen in Figure 4.7. The real detection limit of the GASPILS in the field is dependant to the ground and the atmospheric conditions at the time of the measurement.

To assess the impact of the chopper wheel temperature on the gas detection sensitivity, the chopper temperature has been changed to 290.9°K and a new calibration curve is obtained and plotted as seen in Figure 4.6. The improvement on the sensitivity by decreasing the chopper wheel temperature is clearly demonstrated in the Figure 4.6. This phenomenon is thought to be due to the changes in the vibration-rotational line strength (both relative and absolute) within the filter bandpass.

4.4.1 Ethane Channel Performance

So far the discussion has been confined to the methane channel where the designed sensitivity has been obtained. The ethane channel has also been evaluated and proven to function properly. The electrical noise level is reduced to the level of that in the methane channel. Zero gas balance has

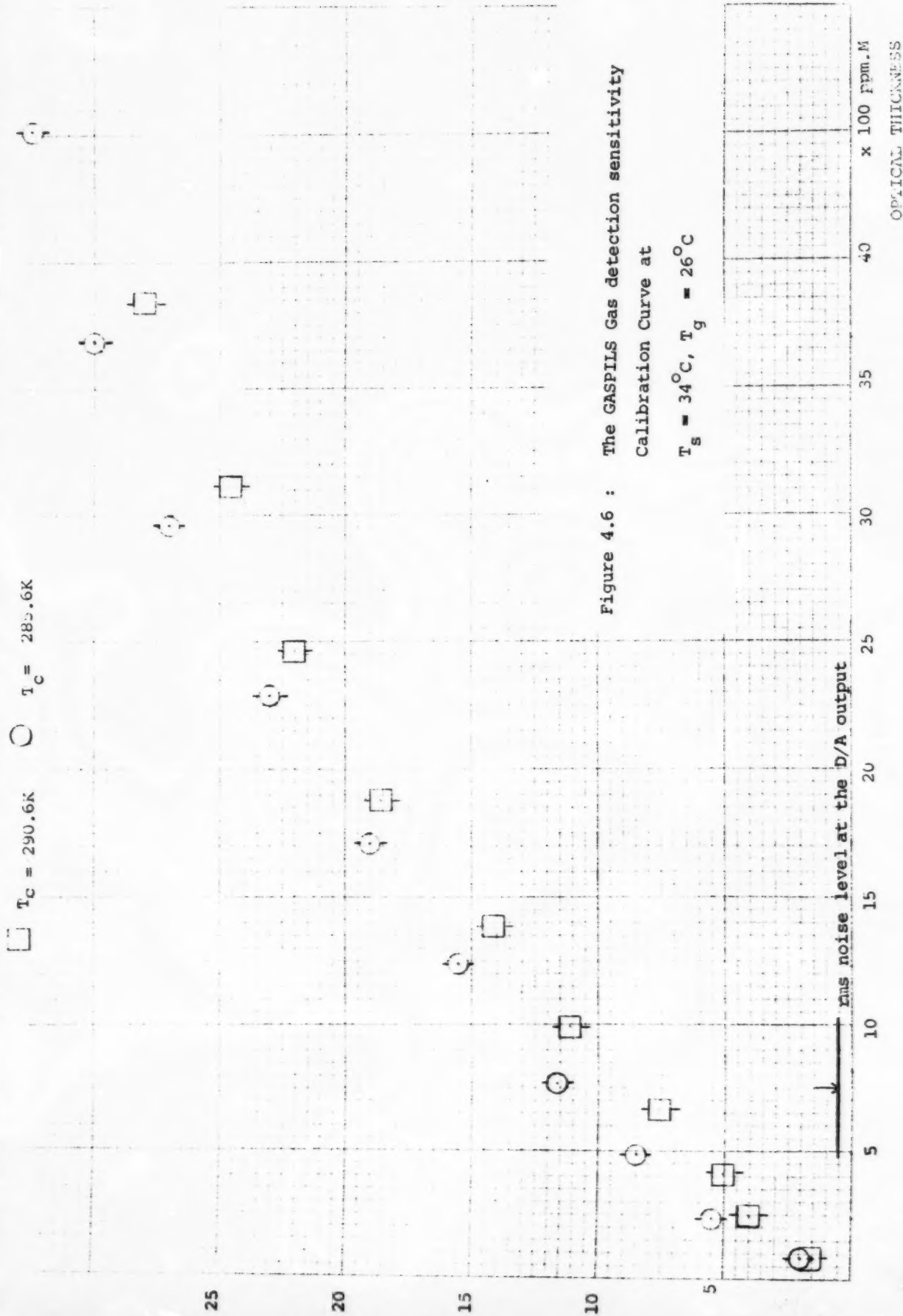


Figure 4.6 : The GASPILS Gas detection sensitivity Calibration Curve at

$$T_s = 34^{\circ}C, T_g = 26^{\circ}C$$

(p.p.m.)

120

100

80

60

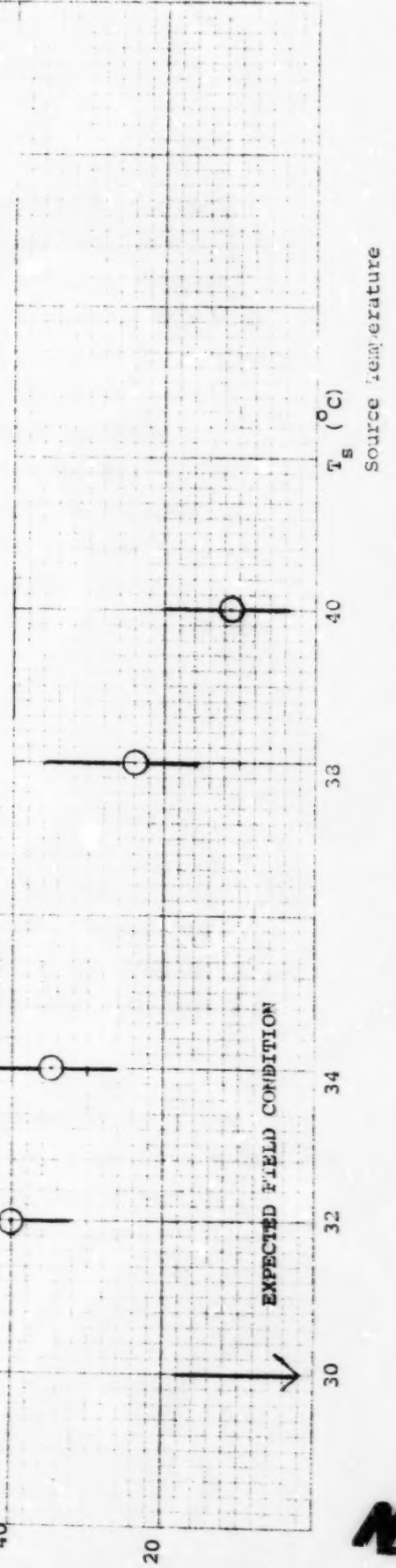
40

20

$T_s = 26^{\circ}\text{C}$

$T_s = 286.4\text{ K}$

Figure 4.7: The GASPILS gas detection limit as a function of the source temperature.
Gas temperature 26°C and Chopper Wheel temperature 286.4 K



has also been obtained to the noise level.

Although the present sensitivity (750 ppm.M) is inferior to the design objective, the cause of this low sensitivity is identified. The newly available published experimental data, shows the band strength is 4.7 times weaker than that assumed in the Phase 1 report. This also implies that a 4.7 times greater optical thickness (or more) is necessary for the optimum correlation coefficient. The GASPILS optics design feature will accommodate such a change without redesigning the optical train but this additional work could not be performed because of cost constraints. An improved gas cell will be fabricated and employed in the field trials. An N_2O gas cell is already proposed (Phase 1 Report) as an alternative to the C_2H_6 gas for one of the flight experiments. The comparison of the field results of C_2H_6 and N_2O is now more important than ever before.

4.5 Stability and Noise Immunity of GASPILS

GASPILS is designed to be immune to mechanical vibration, electromagnetic noise as well as to interference gas. The optical components are rigidly mounted to the sensor frame, and the adjustable components are designed to be tightened after adjustment, (particularly the detector and detector lens assembly). The optical train is assembled rigidly and partially isolated mechanically from the other components to minimize the impact of vibration.

The digital electronics together with the signal processing algorithm employed in the GASPILS design provides good noise rejection for a wide range of frequencies. High frequency noise is filtered by three stages of low-pass filters and the signal averaging algorithm in the digital electronics.



The low frequency noise is rejected by AC coupling and by a signal processing algorithm using the Z-80 microprocessor. The algorithm was initially designed to compensate for the moving field of view effect of ground emissivity change on the gas signal. The assessment of these design features must be carried out in the field evaluation, however, a simple laboratory assessment shows good vibration and EMI immunity of the GASPILS instrument.

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5.0 GUIDE FOR USERS

5.1 Electrical Connection

The instrument is designed to be operated on a 28V DC power. The internal power supply converts the input to $\pm 15V$, $\pm 12V$ and $\pm 5V$ for the entire instrument. The 28V DC is used for the temperature controller, chopper motor speed controller and for a cooling fan. The total electric power required is 300 watts maximum.

The instrument requires 20 minutes of warm-up time before it stabilizes the chopper and gas cell temperature.

5.2 Output Signal Connection

The signals are fed out in a 0-10 volt analog form as well as 7 bit ASC-11 character RS-232 at 300 baud rate. Output signals consist of radiance signals at $7.8 \mu m$ and $12.2 \mu m$, leak-gas signals for methane and ethane, and the ratio of the two gas signals.

The analog output is provided at the 8 pin Bendix connector on the front panel and the pin connection is described in Section 3.3.



The RS-232 output is also provided at the T2 connector on the control panel. This port outputs 7 bit ASCII characters at 300 baud rate. The format of the data is as follows:

Carriage Return

Line Feed

$\overline{\Delta SM}$, $\overline{\Delta SE}$, $\overline{SM}$, $\overline{SE}$, R

These five data values are all given as sign plus four hexadecimal numbers. For further information, refer to Reference I in this report.

5.3 Operation

The power switch is the only control switch on the control panel (See Figure 5.1). The control panel is shown in Figure 5.1. It consists of:

- i) Power switch
- ii) Power input connector
- iii) Analog output multipin Bendix connector
- iv) Digital RS-232 output connector
- v) Power fuse from direct line (28 Volt 6A)
- vi) Power fuse for the dc-dc converter
- vii) Audio alarm to indicate gas-leak
- viii) LED alarm to indicate gas-leak
- ix) LED alarm to indicate overflow in the digital signal processing
- x) Quick connector for the nitrogen gas supply

Proper settings are required at several places inside the instrument to ensure the correct function of the GASPILS sensor. These settings include the zero gas balance adjustment, the cell temperature setting, motor speed setting, delay and sampling period setting, the number of digital averaging selection and the amplifier gain setting. Except for the temperature setting

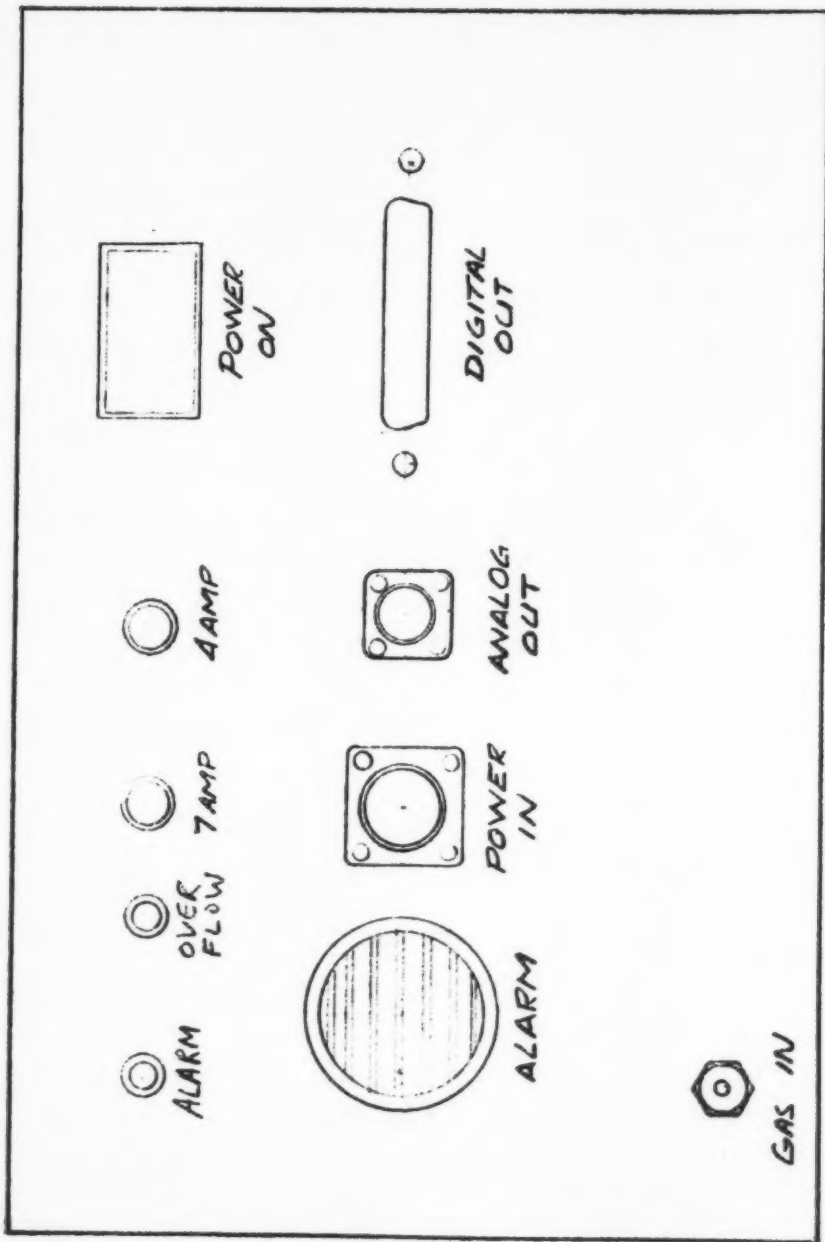


FIGURE 5.1 : Schematics of the GASPILS Control Panel

the motor speed setting and the amplifier gain setting, all other settings are associated with the digital signal processing electronics and are carried out by dip-switches. The details of the procedures for the settings is described in the operating manual. The temperature setting is recommended to be redone when required to maintain the chopper temperature several degrees (5°K) above the environmental temperature. The setting for the number of digital averaging may need re-adjustment depending on the aircraft speed to provide the required spatial resolution.

5.4 Installation

The instrument should be installed in an aircraft with the field lenses directing downward. A separate platform with two holes in front of the field lenses, is recommended to mount the sensor using the attached shock absorber. A high pressure, (1000-3000 psi) nitrogen gas tank approved for the aircraft installation is also required for the Joule-Thomson cryogenic system. The flexible metal hose provided with a pair of quick connectors at both ends shall be used to feed the nitrogen to the Joule-Thomson cooler. The detector should cool in about one minute with a 2000 psi gas supply. (See Figure 5.2)

Since the optics are designed for the infrared bands ($7.8\text{ }\mu\text{m}$ and $12.2\text{ }\mu\text{m}$) only clear holes or a special infrared window are permitted in front of the field lenses. If it is required, the sensor can be installed to look off nadir angle, but care is necessary to protect the sensor from vibration. A chart recorder and a digital output recorder with a timing signal are required to record the output of the sensor for post mission data analysis.

5.5 Maintenance

The sensor is recommended to be stored in a dry, room temperature environment. Excessive humidity may cause the optics components to deteriorate and high temperature may cause a gas cell leak. Care of the detectors

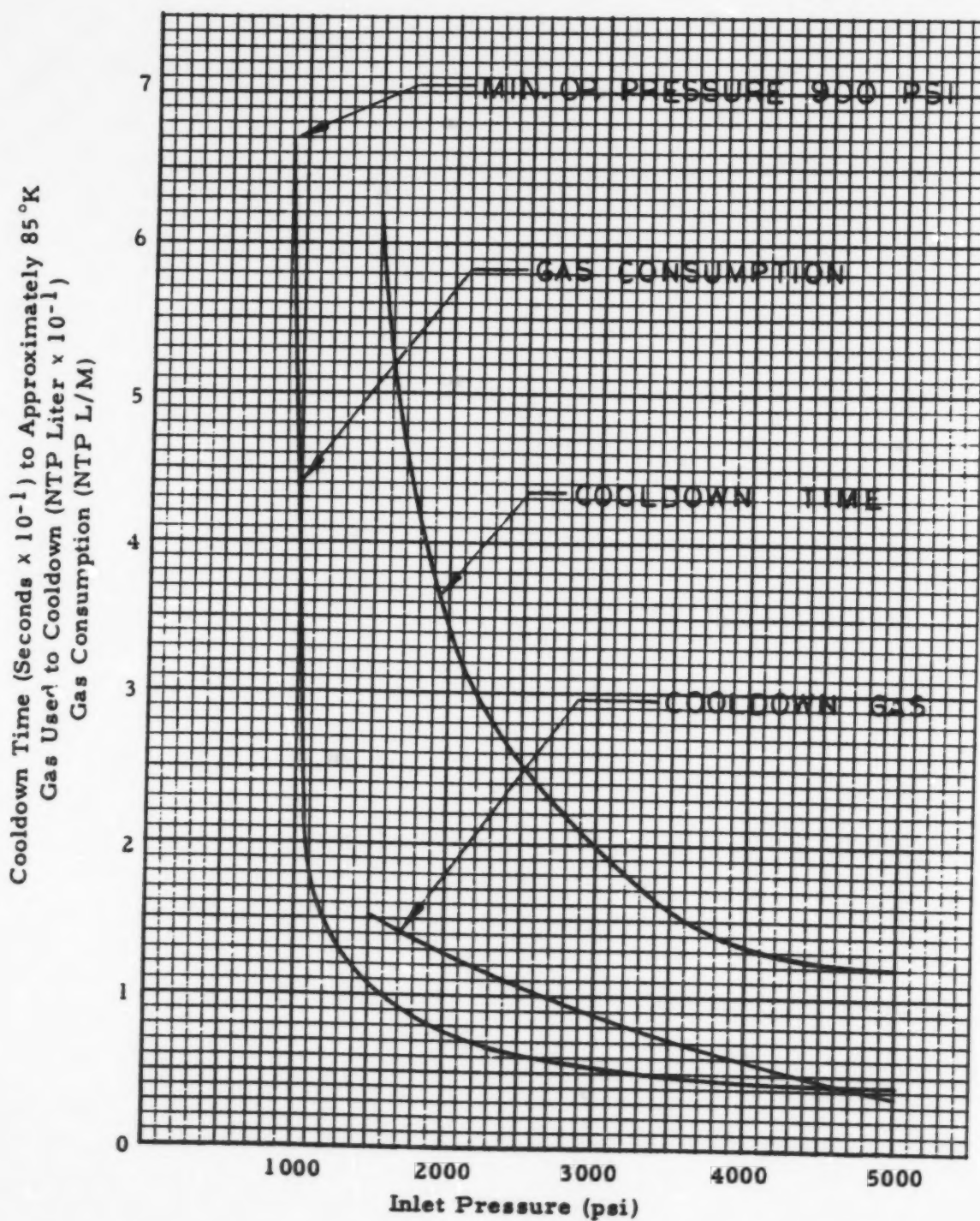


Figure 5.2:
42902-2 Cryostat in 0.2 Watt Flask
Operating on Nitrogen in 25°C Ambient
(1.63 Immersion Depth)

and coolers is as indicated in the SBRC miniature J.T. Cooler Manual provided in the Appendix III.

5.6 Specifications (See Section 1.7)

Principle of Measurement:	gas filter correlation technique
Data Acquisition Rate:	50 data/sec at input
Detection Limit:	70 ppm-m for CH ₄ 750 ppm-m for C ₂ H ₆ 0-10 ⁴ ppm-m
Measurement Range:	8°
Field of View:	28 cm x 46 cm x 56 cm
Dimensions:	25 kg
Weight:	28 v-dc, 300 W
Power Requirements:	-10 to +40C
Operating Temperature:	1) 0-10V analog, 800 Ω output impedance 16 bit resolution gas, radiance for each channel and radiance,
Outputs:	2) all in 7 bit ASC-11 character RS-232 at 300 baud rate for the radiance signals, gas signals and the ratio signal
Gas Consumption for two Joule-Thomson cryogenic systems: (Nitrogen)	0.16 NTP.L/min for 2000 psi inlet pressure after cooling

